



**HAL**  
open science

## Evaluation environnementale multi-échelle des filières agricoles par couplage ACV/MFA

Yazid Charkani

► **To cite this version:**

Yazid Charkani. Evaluation environnementale multi-échelle des filières agricoles par couplage ACV/MFA. Modélisation et simulation. 2022. hal-03739892

**HAL Id: hal-03739892**

**<https://inria.hal.science/hal-03739892>**

Submitted on 28 Jul 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Evaluation environnementale multi-échelle des filières agricoles par couplage ACV/MFA

**Yazid Charkani**

**Responsable pédagogique UTT :**  
Pauline Marty

Master: Imedd

**Semestre:** Printemps 2022

## Résumé

Le stage a été réalisé au sein de l'équipe de recherche STEEP, spécialisée dans la modélisation biophysique de l'économie. L'objectif du stage est d'évaluer l'empreinte environnementale de filières agricoles au niveau national et régional en France. Pour ce faire un travail de couplage et d'harmonisation entre les données de flux de matières basées sur la méthode AFM et les données d'impacts environnementaux basées sur la méthodologie ACV a été réalisé. Une méthodologie d'harmonisation entre ces deux modèles a été proposée et testée sur 4 filières (Blé tendre, Avoine, Mais, Lait). La régionalisation a été testée sur la filière lait, les résultats ont mis en lumière le transfert d'impacts entre territoires due à la consommation finale des habitants.

**Date de soutenance : 02/09/2022**

**Entreprise : INRIA**

**Lieu : Montbonnot saint-martin**

**Responsable : Jean-Yves Courtonne**

## Mots clés

- Recherche appliquée, développement
- Services non marchands (fonction publique)
- Environnement
- Analyse des données – Logiciels

## Remerciements

Ce travail n'aurait pas été possible sans l'encadrement sans faille de Jean-Yves Courtonne et Julien Alapetite, qui m'ont accordé l'autonomie suffisante pour mener à bien le stage et m'ont fait confiance tout au long de ces 6 mois. Je tiens également à remercier toute l'équipe STEEP pour les nombreuses discussions et échanges très enrichissants, qui ont contribué à forger mon esprit critique et à remettre en question mon rapport à la science et à la recherche de façon large. Merci à Baptiste de Goer de Herve pour son aide en informatique. Enfin, je remercie Sabrina Brullot sans qui je n'aurais peut-être jamais connu cette équipe de recherche si unique et humble.

## Contents

<b>REMERCIEMENTS .....</b>	<b>2</b>
GLOSSARY: .....	5
<b>RESUME EN FRANÇAIS .....</b>	<b>6</b>
CONTEXTE DU STAGE .....	6
PROBLEMATIQUE SCIENTIFIQUE ET OBJECTIFS .....	8
METHODOLOGIE.....	9
<i>Analyse de cycle de vie</i> .....	9
<i>Analyse de flux de matière</i> .....	10
<i>ACV territoriale</i> .....	10
<i>Réponses méthodologiques</i> .....	10
DEROULEMENT DU STAGE ET MISSIONS.....	14
RESULTATS .....	16
<i>Au niveau national</i> .....	16
<i>Au niveau régional</i> .....	17
<i>Analyse de sensibilité</i> .....	18
LIMITES ET PERSPECTIVES.....	19
CONCLUSION.....	20
<b>INTRODUCTION: .....</b>	<b>21</b>
CONTEXT.....	21
RESEARCH QUESTIONS:.....	26
<b>METHODOLOGY: .....</b>	<b>28</b>
LIFE CYCLE ASSESSMENT: THE CORE METHODOLOGY.....	28
MATERIAL FLOW ANALYSIS:.....	30
TERRITORIAL LIFE CYCLE ASSESSMENT.....	31
THE CASE STUDIES: .....	32
<i>System boundaries</i> .....	32
<i>LCA Databases used</i> .....	32
<i>Lca impact assessment methods used</i> .....	32
<i>Functional unit</i> .....	33
<i>General assumptions and parameters:</i> .....	33
COUPLING MFA AND LCA: A PROPOSAL FOR FOOD SUPPLY CHAINS .....	34
<i>The disaggregation question: towards a modular approach</i> .....	37
.....	37
<i>Multi-output modelling harmonisation</i> .....	38
<i>How to deal with multi-allocation processes?</i> .....	41
<i>Impacts transfer of final consumption</i> .....	43
<b>RESULTS: .....</b>	<b>44</b>
NATIONAL SCALE FOOD SUPPLY CHAINS: THE CASE OF CEREALS .....	44
<i>Contribution analysis</i> .....	46
MULTI-SCALE ASSESSMENT: THE CASE OF THE DAIRY INDUSTRY NATIONAL AND REGIONAL IMPACTS.....	47
<b>NATIONAL DAIRY</b> .....	<b>47</b>
<b>REGIONAL</b> .....	<b>48</b>

SENSIVITY ANALYSIS.....	49
<i>Regarding LCIA methods</i> .....	49
<b>LIMITS AND DISCUSSIONS:</b> .....	<b>50</b>
PERSPECTIVES: .....	52
<b>CONCLUSION</b> .....	<b>53</b>
<b>BIBLIOGRAPHY</b> .....	<b>54</b>
<b>APPENDIX 1 : SANKEY DIAGRAM OF THE SOFT WHEAT FOOD SUPPLY CHAIN</b> .....	<b>58</b>
<b>APPENDIX 2: SUPPLEMENTARY INFORMATION'S FOR THE SOFT WHEAT FSC</b> .....	<b>59</b>
<b>APPENDIX 3 : SUPPLEMENTARY INFORMATION'S FOR THE CORN FCS</b> .....	<b>60</b>
<b>APPENDIX 4 SUPPLEMENTARY INFORMATION'S FOR THE OATS FCS</b> .....	<b>61</b>
<b>APPENDIX 5 : SUPPLEMENTARY INFORMATION'S FOR THE DAIRY FCS</b> .....	<b>62</b>

## Table of figures

<b>Figure 1</b> the context of the internship.....	21
<b>Figure 2</b> : the contribution of the work to scalable project.....	25
<b>Figure 3</b> Physical scale différence SC-MFA/LCA.....	26
<b>Figure 4</b> Temporalities in LCA/MFA.....	26
<b>Figure 5</b> Research framework .....	27
<b>Figure 6</b> LCA scopes .....	28
<b>Figure 7</b> The four phases of an LCA study based on ISO 14040.....	29
<b>Figure 8</b> Simple MFA model.....	30
<b>Figure 9</b> FSC LCA Method integration between LCA and MFA.....	31
<b>Figure 10</b> Framework for quantifying the environmental footprint related to both consumption and production side of an agrifood sector .....	34
<b>Figure 11</b> procedure to calculate the embedded transport impacts of import/exports goods .....	36
<b>Figure 12</b> The farmgate to plant gate scope used, represented in the red frame .....	37
<b>Figure 13</b> Differences in multi-output modelling between MFA and LCA .....	39
<b>Figure 14</b> Agrifootprint data modelling for multifunctional processes .....	40
<b>Figure 15</b> ACYVIA inventory modelling example.....	40
<b>Figure 16</b> Milling process diagram in ACYVIA .....	41
<b>Figure 17</b> Sensivity analysis Milling by-products.....	42
<b>Figure 18</b> Sensivity analysis flour wheat.....	42
<b>Figure 19</b> Contribution analysis of the soft wheat FSC By sectors and production destination .....	46
<b>Figure 20</b> Contribution analysis of the soft wheat FSC on non-climate change impacts.....	46
<b>Figure 21</b> Sensivity analysis flour wheat.....	47
<b>Figure 22</b> Contribution analysis of the IDF dairy FSC.....	48
<b>Figure 23</b> Contribution analysis Bretagne Dairy FSC.....	49

## Table of tables

<b>Table 1</b> The three principles for allocating responsibility through the value chain .....	35
<b>Table 2</b> Output flows values mismatch for the starch soft wheat sector .....	39
<b>Table 3</b> variability analysis of the impacts according to the multi-output physical distribution MFA/LCA .....	42
<b>Table 4</b> Soft wheat results, ER : extended responsibility.....	44
<b>Table 5</b> Corn results ER: extended responsibility.....	45
<b>Table 6</b> Oats Food supply chain impacts results ER: extended responsibility.....	45
<b>Table 7</b> the embedded impacts of transports in imported wheat grains .....	47
<b>Table 8</b> National dairy Impacts.....	47
<b>Table 9</b> Sensivity analysis regarding LCIA methods.....	49

## Glossary:

**Food supply chains (FSC):** we use the term supply chain based on the definition of the FAO “a food supply chain Consists of a connected series of activities encompassing the primary production of food from crops, livestock, forestry, fisheries and aquaculture; and the value-adding activities of storage, transportation, processing; wholesale and retail distribution” (FAO, [2021](#)).

**Product systems:** A product system is a fundamental concept in Life cycle assessment, it’s the main model of system/ product studied, which contains the different unit processes<sup>1</sup> represented by datasets and their interconnections.

**Sankey diagrams:** Sankey diagrams are a type of diagrams in which the width of the arrows is proportional to the flows, it is used to better represent the weight of energy/mass flows in a system. The International energy agency has created an interactive web-app to visualise the energy balance of the world ([Link](#))

---

<sup>1</sup> A unit process is the most disaggregated data in a lca, see ISO 14040(2006a) for a more detailed definition.

## Résumé en Français

Cette section offre une synthèse des missions réalisées durant le stage, de la méthodologie employée ainsi que des résultats obtenus. Les développements techniques et les approfondissements méthodologiques et conceptuels sont à retrouver dans le corps du document en anglais.

### Contexte du stage

Le stage s'est déroulé au sein de l'Inria (institut de recherche sur les sciences du numériques) Grenoble-Alpes, plus spécifiquement au sein de l'équipe de recherche STEEP. L'Inria est l'un des 6 établissements publics à caractère scientifique et technologique français, créée en 1967, il a pour missions le développement de la recherche et de la valorisation en sciences et techniques de l'information et de la communication.

L'équipe STEEP a pour objet la modélisation de l'interaction entre la société et l'environnement à travers deux prismes, l'environnement et les risques systémiques, ces deux angles définissent l'orientation thématique des deux axes de l'équipe :

**L'axe AST (alternatives sociotechniques) :** dont l'objet est la modélisation biophysique de l'économie, à l'intersection entre l'économie écologique et l'étude du métabolisme sociale.

**L'Axe RSG (Risques systémiques globaux) :** basé sur les travaux de modélisation global et systémique (Meadows, [1972](#)), l'axe étudie la vulnérabilité de nos sociétés modernes au regard de leur complexification croissante.

Les deux axes partagent une approche systémique et pluridisciplinaire pour aborder ces questions. Le stage a été intégré à l'axe AST, dont l'objectif à terme est de pouvoir proposer des outils d'aides à la décision à des citoyens ou politiques pour les accompagner dans le choix d'une alternative sociotechnique. Cette dernière se définit comme un ensemble de mode de consommation et de production ancrée dans un contexte économique, politique et territorial et qui nécessite à la fois une dimension technique et sociale. L'implémentation d'un méthaniseur est un exemple d'une AST, en effet cette décision implique naturellement une dimension technique qui va définir sa faisabilité (volume de matière méthanisable, potentiel de valorisation de l'énergie produite etc.) mais également une dimension sociale associée à l'acceptabilité sociale du projet par les riverains et au changement de l'activité des agriculteurs du territoire (moins orienté vers la production alimentaire).

Ce stage s'inscrit également dans le projet de recherche Scalable qui met en collaboration un ensemble d'acteurs publics (INRAE-INRIA-AUREE) et privé (Terriflux), et dont l'équipe STEEP est partenaire. Le projet a pour objectif d'évaluer la vulnérabilité des territoires au regard du métabolisme de leurs filières agricoles. Par filières agricoles nous nous référons à la définition de la FAO ([2021](#)) « une filière agricole est un ensemble d'activités liées qui intègre la production primaire de produits issues de cultures, d'élevage, de pêche ou de sylviculture, la transformation, le stockage ainsi que la distribution ». Les vulnérabilités sont distinguées en deux types, les vulnérabilités environnementales (évalué par les pressions générées par leurs filières) et les vulnérabilités socio-économiques (évaluées par la structure des flux économiques). Il a été décidé d'évaluer la dimension environnementale de la vulnérabilité selon deux approches de pressions<sup>2</sup> :

- Les empreintes Energie/Azote, qui font l'objet d'un autre stage effectué par Alexandre Pannier et se situe dans la continuité des travaux de S.Harchaoui ([2015](#)) sur l'évolution de la capacité de charge des systèmes alimentaires au vu des flux d'azote et d'énergie.

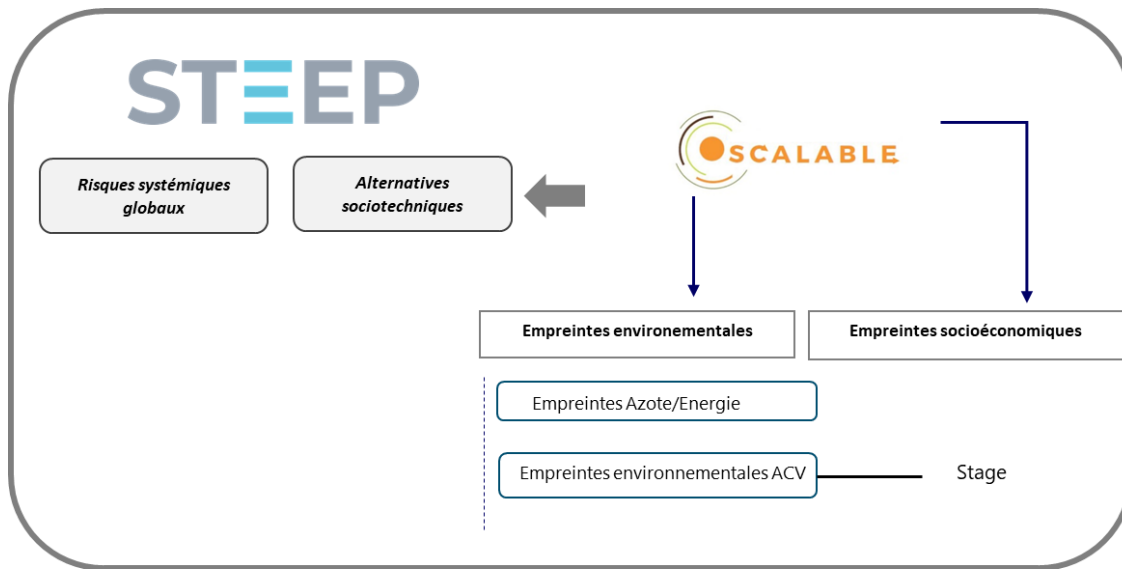
---

<sup>2</sup> Une pression environnementale est une charge environnementale absolue, indépendante de la capacité de charge d'un milieu.

Le travail est orienté vers deux axes, la représentation des flux E/N associés à chaque filière agricole sous la forme de diagrammes de Sankey<sup>3</sup> d'une part et l'étude de l'autosuffisance (à travers le bouclage des flux) des filières via des indicateurs d'autre part.

- Les empreintes basées sur les indicateurs issues de l'approche d'analyse de cycle de vie, qui est le sujet de ce stage et qui diffère de la première approche par son périmètre élargi intégrant plus d'indicateurs (toxicité humaine par exemple).

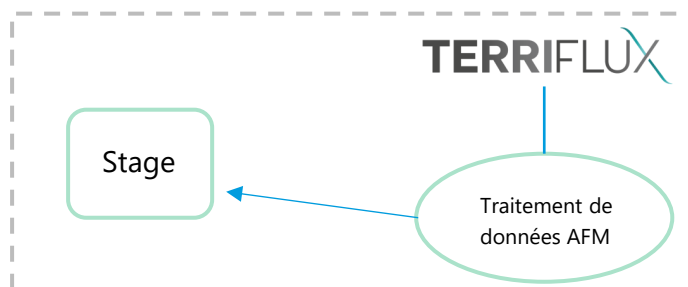
En guise de synthèse, le diagramme ci-dessous présente le positionnement du stage au sein des différentes structures :



**Contexte du stage**

Les analyses de flux de matières des filière agricoles ont été produites dans le cadre du projet AF-filière<sup>4</sup> (2017) en collaboration avec le groupe d'intérêt scientifique « Avenir élevage » et de Terriflux, qui a pris en charge le co-encadrement du stage.

[Terriflux](#) est une start-up créée par Julien Alapetite et hébergée à l'Inria dont l'objectif est de valoriser la méthode AFM filières développée en collaboration avec Jean-Yves Courtonne, au niveau du traitement de données (réconciliation de données de flux) et de la visualisation sous forme de diagramme de Sankey, l'entreprise est à l'origine de [Opensankey](#)<sup>5</sup>, un outil en ligne de visualisation multi-échelle des flux d'une filière.



**Lien avec terriflux**

<sup>3</sup> Voir annexe 1 pour un exemple d'un diagramme de Sankey

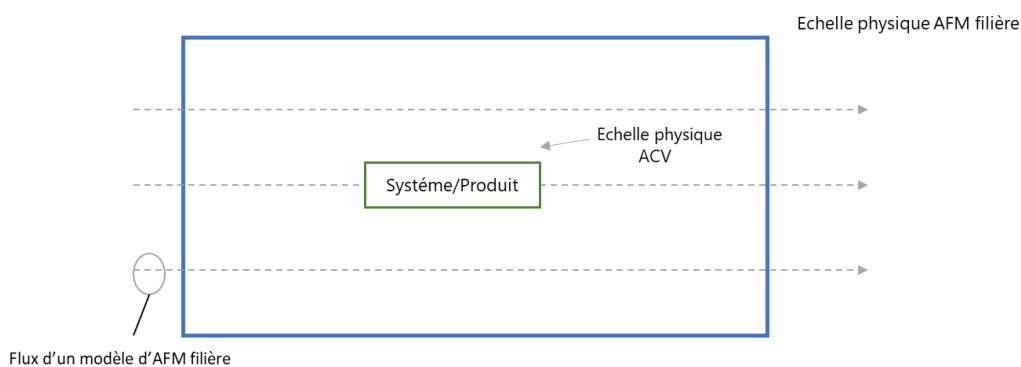
<sup>4</sup> <https://www.flux-biomasse.fr/>



## Problématique scientifique et objectifs

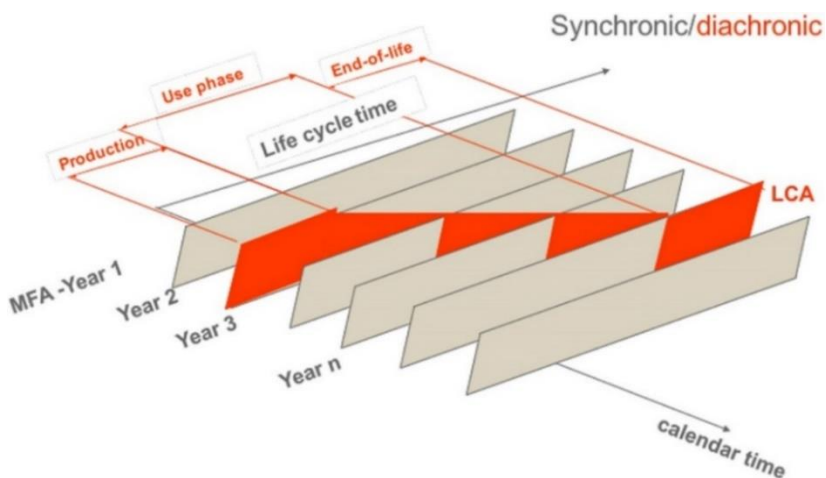
L'objectif du stage est de proposer une méthodologie de couplage de la méthode ACV avec les analyses de flux de matière (AFM), les filières agricoles figureront comme cas d'études de la méthode, qui sera répliquable à d'autres filières<sup>6</sup>.

Le principal défi méthodologique à résoudre a été d'harmoniser les périmètres physiques et temporels des deux méthodes, en effet comme l'a souligné Birat (2015), l'analyse de cycle de vie est une méthode orientée produit, destinée à évaluer des systèmes à une petite échelle physique (échelle micro), tandis que l'AFM est principalement utilisée pour étudier des systèmes à grande échelle (Macro), à l'échelle nationale (EW-MFA), urbaine (métabolisme urbain), ou des unités industrielles. Cette différence de périmètre de modélisation peut créer des incohérences entre les deux méthodes, spécifiquement au niveau des procédés multi-output, très présents dans le secteur agricole, dont l'impacts des produits qui y sont issues, sont modélisés par la méthode ACV en suivant des règles standardisées (ISO. 2006b) d'affectation des impacts.



### Différence d'échelle physique ACV/AFM

Concernant l'échelle temporelle, l'AFM se base sur une approche synchronique (F.Le Gallou et al.1991), elle se focalise sur le fonctionnement d'un système sur une durée définie (essentiellement un an), alors que l'ACV repose sur une approche diachronique, autrement dit l'aspect évolutif et dynamique du système est considéré. Ainsi, l'ACV inclut généralement toutes les étapes du cycle de vie d'un système et de ses intrants (électricité depuis l'extraction des matières premières nécessaires, production des engrais etc.), il est rare que les deux échelles temporelles convergent (AFM/ACV), notamment en raison de l'inclusion du cycle de vie des intrants.



Différence d'échelle temporelle AFM/ACV  
Source : Birat 2015

<sup>6</sup> Filière définie comme un ensemble d'acteurs regroupés autour d'une matière première commune.

La question de recherche principale du stage est la suivante :

### **Quelle méthodologie appliquer pour permettre un couplage cohérent entre les méthodes ACV et AFM ?**

Cette question générale peut être répartie en sous-questions plus spécifiques, basées sur les incohérences de modélisation entre les deux méthodes :

- Au niveau de l'harmonisation du périmètre temporelle : **Comment désagréger l'empreinte environnementale d'une filière agricole à partir de données ACV orientées produit ?**
- Au niveau de l'harmonisation du périmètre physique : **Comment résoudre les incohérences de modélisations des procédés multi-output ? – Comment intégrer l'empreinte des flux d'imports/exports ?**

La résolution de ces sous-questions permettra d'apporter plus aisément des éléments de réponse à la question de recherche globale.

## Méthodologie

### Analyse de cycle de vie

L'analyse de cycle de vie est une méthode systémique, multicritère et exhaustive d'évaluation environnementale. Standardisée au milieu des années 90 (ISO, [2006a](#), [2006b](#)), elle est devenue au fil des années une méthode de référence pour l'évaluation environnementale des produits/systèmes, elle se caractérise par son périmètre temporel élargi, intégrant l'ensemble du cycle de vie d'un système (de l'extraction des matières premières à la fin de vie) ainsi que la prise en compte d'un maximum d'indicateurs d'impacts environnementaux. Une ACV est un processus itératif qui se déroule en 4 phases :

1. **La définition des objectifs et du périmètre** : cette première étape est cruciale dans une étude ACV, c'est durant cette phase que les paramètres structurants vont être déterminés, notamment les périmètres, temporel (la partie du cycle de vie qui est incluse) et physique (les éléments inclus dans le système étudié, par exemple l'inclusion/exclusion de l'infrastructure). Ainsi que l'unité fonctionnelle, qui représente une unité de référence de la performance du système sur laquelle les impacts sont imputés, elle est obligatoire pour permettre la comparabilité des résultats avec d'autres études.
2. **L'inventaire du cycle de vie** : étape de comptabilisation des intrants au système (énergie, eau, matière première) et de ses émissions vers la biosphère.
3. **L'évaluation des impacts** : une fois l'inventaire réalisé les émissions absolues du système seront converties en indicateurs d'impacts à travers une procédure de caractérisation, il existe une multitude méthode de caractérisation des impacts (Recipe, EF, CML..).
4. **L'interprétation** : enfin, une dernière étape consiste à évaluer les résultats au regard des hypothèses prises en amont à travers une analyse de sensibilité, et à analyser la signification des résultats à travers une analyse de contribution, mettant en lumière les processus/ étapes les plus contributeurs aux résultats finaux. C'est également durant cette phase que les recommandations de réduction des impacts sont formulées pour les décideurs.

## Analyse de flux de matière

L'analyse de flux de matière (*MFA* en anglais), est une des principales méthodes d'analyses environnementales issues de l'écologie industrielle, c'est la méthode de référence pour évaluer l'aspect biophysique d'une économie. Selon l'objet étudié, on peut distinguer deux types d'AFM : MFA classique pour les matières et la SFA (substance flow analysis) pour les substances chimiques<sup>7</sup> (cuivre, carbone, azote etc..). La méthode a également été étendue aux flux d'énergie. Au niveau conceptuel, une AFM est très similaire à une ACV, les deux méthodes partagent les notions de frontières de systèmes (qui délimite le système étudié), processus (qui a pour fonction la transformation des flux) et flux entrants/sortants, la seule différence réside dans le périmètre (des systèmes macro pour l'AFM et micro pour l'ACV) et la comptabilisation de la variation de des stocks pour l'AFM.

Le sujet du stage se positionne au sein l'approche AF filière (*SC-MFA*).

L'AF filières telle que proposée par Courtonne et Alapetite (2016) diffère de l'AFM classique par sa finalité, plutôt économique, qu'environnemental, en effet l'objectif principal d'une Analyse des flux d'une filières est d'informer ses acteurs de la structure des flux au sein de la filière, l'amélioration des performances environnementales est un objectif secondaire. Une autre différence est la souplesse méthodologique, l'AFM classique impose le respect du principe d'équilibre de masse entre les inputs et outputs des processus, principe qui peut être outrepassé en AF filière. Un exemple d'une AFM du blé tendre est présenté en Annexe 1.

## ACV territoriale

Pour faire face à l'inadéquation de l'ACV à des Macro-systèmes, Loiseau (2018) a proposé une extension méthodologique de l'analyse de cycle de vie classique aux territoires. Loiseau (2018), distingue deux types d'ACV-T :

Type A : basé sur le travail de thèse de Laurent (2015), il concerne des systèmes ancrés dans des territoires, par exemple les méthaniseurs.

Type B : concerne l'évaluation des impacts de toute l'activité d'un territoire, distingué par production/consommation.

L'ACV-T a été étudié au début du stage, en partant du principe qu'une filière agricole peut être ancrée dans un territoire et donc de fait est territorialisable. Dans les faits les chaînes de production agro-alimentaires sont souvent déconnectées géographiquement avec des acteurs dispersés sur différents territoires. Cependant, avec l'émergence des circuits courts, ce type d'évaluation serait théoriquement pertinent, si on se limite à la chaîne de production d'un seul produit (la farine par ex).

## Réponses méthodologiques

### *Comment désagréger le périmètre temporel d'une ACV ?*

Plusieurs périmètres sont utilisés dans les études ACV, le plus commun est du berceau à la tombe (cradle to gate), considéré comme une ACV complète incluant tout le cycle de vie. La majeure partie des données de la base Agribalyse sont ainsi modélisées avec ce périmètre. Dans une approche filière, utiliser des données cradle to gate conduirait à un double comptage, en effet les données intègrent les impacts de toutes les étapes de la chaîne de production en amont, ce qui ne permet pas d'avoir une vision de pression par étape de production. Afin de séparer les empreintes de chaque étape de la chaîne de production et d'éviter le double comptage, j'ai proposé de transformer le périmètre des données de produits finis « Cradle to Gate » au « farm-gate to gate » de la sortie de la ferme à la sortie de l'usine de transformation. Un nouveau périmètre excluant la phase de production à la ferme.

---

<sup>7</sup> Une substance est une composant d'une matière.



### Nouveau périmètre ACV proposé Farmgate-to-gate

En fonction de l'objectif visé et du volume de données, ce changement de périmètre peut s'opérer selon 3 voies différentes :

- **Pour garantir la maintenabilité** : dans les logiciels d'ACV classiques (OpenLca, Simapro..), la donnée est dupliquée sans l'intrant principal brut (la matière première issue de la phase de production), cette nouvelle version représentera une version « Farm-gate to gate » personnalisée. L'avantage est de pouvoir aisément identifier et différencier les différents périmètres et de faciliter la prise en main des données par un utilisateur externe, mais cela nécessite un coût supplémentaire en termes de temps.
- **La solution la plus rapide** : Sur OpenLCA<sup>8</sup>, la procédure de calcul des impacts d'un produit passe obligatoirement par la création du Productsystem<sup>9</sup>, il est possible de séparer à cette étape la donnée ACV de l'intrant principal de la donnée produit en supprimant la connexion entre c'est deux données, sur l'onglet « Model graph ». Cette procédure est environ 6 fois plus rapide que la duplication de donnée (<10s contre en moyenne 1 minutes).
- **La solution automatisable** : Il est possible d'automatiser cette procédure à travers l'approche Modular LCA développée par B.Steubing et al (2015), qui consiste à structurer les données d'un modèle ACV en modules interchangeables. Cette approche nécessite l'utilisation d'Activity browser, un logiciel avancé en ACV.

### Comment harmoniser la modélisation multi-output des deux méthodes ?

L'harmonisation des procédés multi-output des deux modèles a été le principal verrou méthodologique du stage. A première vue, calculer l'impact environnemental d'un produit dans un modèle AFM à partir de données ACV ne nécessiterai qu'une simple multiplication entre la valeur du flux (AFM) et l'impact unitaire du produit (ACV). Cela serait parfaitement exact pour des procédés mono-produits (ne produisant qu'un seul produit en sortie) ne nécessitant pas de procédure d'affectation.

Dans le cas de procédés multi-output (produisant plusieurs flux en sortie), qui représentent la majorité des procédés de transformation agricoles (meunerie, amidonnerie, fromagerie, industrie du sucre etc.). Il est nécessaire de répartir l'impact total du procédé sur ses flux sortants, la norme ISO définit une procédure hiérarchique de gestion de cette situation (voir p38. pour plus de détails). La stratégie la plus utilisée est l'allocation économique où les impacts sont répartis selon la valeur économique de chaque produits/co-produits. Etant donnée que les impacts sont exprimés par rapport à une unité fonctionnelle (une tonne par ex) une deuxième étape de normalisation est requise. Ainsi l'équation d'allocation des impacts d'un procédé à un produit est la suivante :

$$\text{Impact produit } x = \text{impact total du procédé } A \times \text{coefficient d'allocation} \times \text{1/coefficient de rendement}^{10}$$

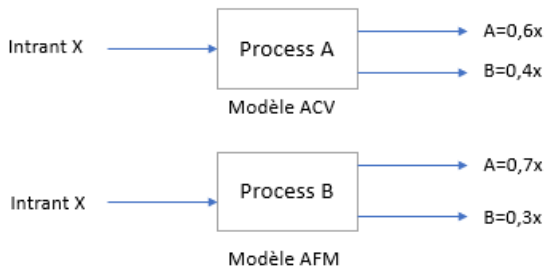
Allocation Normalisation

<sup>8</sup> Logiciel open-source d'ACV, principal concurrent du logiciel leader simapro. [Lien](#)

<sup>9</sup> Un Product system est un concept fondamental en ACV et désigne un semble de processus unitaire liées par des flux (de matière, d'énergie) et qui contribuent à l'atteinte de l'unité fonctionnelle.

<sup>10</sup> Le rapport entre la valeur du flux sortant et l'intrant principal, par exemple 750kg de farine pour 1 tonne de blé en entrée en meunerie revient à un coefficient de rendement de 0.75 pour la farine.

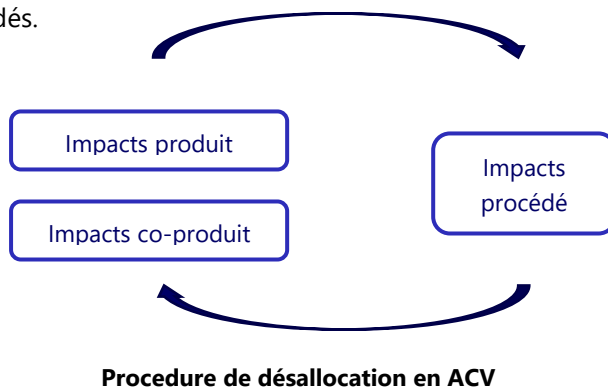
Le problème se pose dans le troisième terme de l'équation, en effet les deux méthodes modélisent les procédés multi-output différemment avec une répartition physique qui peut varier du simple au double et parfois des flux non modélisés. Prenant l'exemple suivant pour illustrer les conséquences de cette différence :



Le process A et B représentent le même procédé industriel, modélisé par les deux méthodes avec des coefficients de rendement légèrement différents. Basé sur les données ACV, prenant une unité du produit A (une unité est équivalente à X, une unité d'intrans) avec un impact de 200 kg d'équivalent co2 et une unité du produit B avec un impact de 150 kg d'équivalent co2. Dans le modèle ACV l'impact du process global serait ainsi de 180kg co2 eq alors

qu'elle est de 185 kg co2 eq pour le modèle AFM, une différence de 2.7% qui au vu des volumes de flux des filières (milliers à millions de tonnes) peut être significative en termes d'émissions absolues. Au-delà, des flux sont parfois manquants dans l'un des modèles.

Pour résoudre cette incohérence, nous proposons de passer de données ACV produits (dont les impacts leurs sont déjà allouées) à des données procédés (pré-allocation), cela permettra d'outrepasser ces incohérences de modélisation des procédés, en effet les incohérences résident principalement au niveau des flux, les secteurs correspondent globalement entre les méthodes. Cette procédure de « désallocation » est détaillée en page 39-40. Il est à noter que cette problématique est fortement dépendante de la construction initiale de la base de données ACV, par exemple les données issues de la base Agrifootprint<sup>11</sup> ont été construites dans une perspective « procédés » et produits, ce qui permet d'éviter un travail supplémentaire de reconstitution de données procédés.



**Procédure de désallocation en ACV**

### L'empreinte triple approche

L'Analyse de flux de matière est une approche duale (consommation/production), ainsi à partir des données de flux nous pouvons quantifier plusieurs types d'impacts, nous en proposons principalement 3 approches d'impacts :

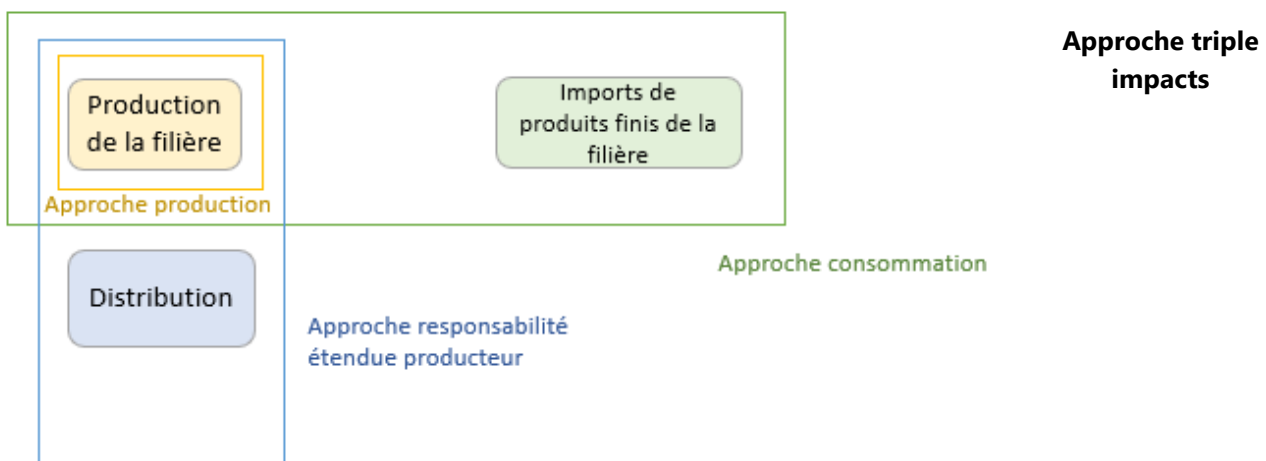
**L'approche production-based :** Une quantification des impacts de la production totale de la filière sur une année, incluant la production destinée à l'export.

**L'approche consumption-based :** qui se rapproche du concept de consommation apparente<sup>12</sup>, c'est la somme des impacts de la production totale d'une filière moins la différence entre les impacts de l'imports des produits finis de la filière et de l'exports, il est à noter que l'impact du transport des flux importés/exportés est considéré dans le calcul. Cette approche permet de mettre en lumière les impacts associés à la consommation d'un groupe de produits dans un territoire.

<sup>11</sup> <https://blonksustainability.nl/tools/agri-footprint>

<sup>12</sup> Pour une définition voir [ce lien](#).

**L'approche Extended responsibility :** Cette approche est une extension de la première, incluant en plus le transport international des produits exportés par la filière nationale. En effet comme les AFM intègrent également les flux internationaux, la question s'est posée pour savoir à qui on attribue les impacts dues au transport des flux exportés, d'autant que pour certaines filières (blé tendre, lin etc.) l'export est très significatif. Nous nous sommes basé sur le principe « Income-based » pour l'allocation de la responsabilité des impacts tout au long de la chaîne de valeur (Weidema et al. [2021](#)), suivant ce principe les impacts sont attribués aux acteurs ayant le plus bénéficié économiquement de l'échange « Beneficiary pays » (ceux en capacité de payer pour la compensation du dommage). Au niveau de la littérature scientifique, la phase distribution a été intégrée dans une étude de 2015 sur l'industrie agro-alimentaire du sucre au Mexique (Guerça et al. [2015](#)).



### Transferts d'impacts

L'approche duale des AFM permet également de calculer le transfert d'impacts entre territoires dû aux imports de produits finis pour la consommation finale de leurs habitants. Ce n'est pas de la spatialisation d'ACV à proprement parler (Nitshelm et al. [2016](#)), mais reste une approximation du phénomène de transfert d'impacts.

Deux indicateurs ont été proposés :

$$\text{Le taux de transfert d'impacts} = \frac{\text{impacts de la Consommation finale des produits de la filière} - \text{impacts de la production de la filière}}{\text{Impacts de la Consommation finale des produits de la filière}}$$

Si l'indicateur est positif, cela indique que la consommation finale du groupe de produit de la filière dans le territoire induit des impacts environnementaux hors-territoire, à l'opposé si l'indicateur est négatif cela indique que le territoire subit (internalise) les impacts environnementaux dûs à la consommation finale d'autres territoires. Dans le premier cas le territoire est importateur net, dans le deuxième il est exportateur net et auto-suffisant dans le type de produits étudiés. En termes de vulnérabilité le premier cas indique une dépendance physique alors que le deuxième montre une dépendance économique due aux exports.

L'une des faiblesses de cet indicateur est sa non-prise en compte des impacts dûs à la production des intrants, ainsi un deuxième indicateur est proposé pour inclure le transfert d'impacts dû aux intrants divers (alimentation animale, production d'engrais.). Cela est possible à condition que l'inventaire de cycle de vie ait une résolution spatiale suffisante<sup>13</sup> (au moins continentale).

$$\text{Taux de transferts d'impacts affinée} = \frac{\text{Impacts de la consommation finale de la filière} - (\text{impacts de la production} - Pt)}{\text{Impacts de la consommation finale des produits de la filière}}$$

<sup>13</sup> Les données Agribalyse pour l'élevage par exemple

Où Pt est la part des impacts qui se produisent sur le territoire. Il est à noter que le résultat est à titre illustratif les ICV<sup>14</sup> ne sont pas suffisamment spatialisés pour permettre un traçage géographique précis des flux et de faits des impacts.

## Déroulement du stage et missions

Le stage s'est déroulé à un rythme de télétravail partiel (2-3 jours hebdomadaires), encadré par Jean-Yves Courtonne et Julien Alapetite, à une fréquence d'une réunion hebdomadaire.

Cette expérience peut être répartie en trois phases distinctes :

- **Une première phase de prise en main** de la méthode AFM filières et de lectures bibliographiques au sujet de l'ACV territoriale et agricoles a marqué le premier mois du stage, cette période a permis d'affiner la problématique et de recadrer le travail de l'ACV-T vers le couplage des modèles.
- **Une deuxième phase opérationnelle**, de quantification des empreintes environnementales des filières. Au total 4 filières ont été étudiées, 3 grandes cultures végétales et une filière animale (Blé tendre, Avoine, Mais et lait). Le travail a suivi une démarche itérative entre quantification et développement méthodologique, en effet la première étape a été d'identifier les données d'analyse de cycle de vie les plus appropriées aux catégories de flux de matières des modèles AFM, au niveau de l'étape de la production agricole à la ferme, un choix a dû être fait entre plusieurs données ACV distinguées par les pratiques culturales. Concernant les étapes de transformation, j'ai rencontré quasi-systématiquement des incohérences entre les deux modèles dues principalement à des niveaux d'agrégation différents (mais également à cause d'incohérences internes à la base Agribalyse), ce qui m'a poussé à développer des réponses méthodologiques afin de réduire les incohérences. Ainsi le travail a été ponctué d'un va et vient entre le traitement de données et l'avancement méthodologique.
- Suite à la quantification des empreintes nationales des différentes filières, **une dernière phase d'affinage et de vérification des résultats a été entamée fin mai**, à partir d'une ancienne étude interne sur la régionalisation des impacts de la production de lait, la filière lait a pu être régionalisée, intégrant les étapes de transformations avec des méthodes d'impacts ACV mise à jour. Des analyses de sensibilité ont également été réalisées pour évaluer d'une part la sensibilité des résultats à la méthode d'impacts et d'autre part la sensibilité des résultats d'impacts unitaires des produits au type de modélisation.

J'ai pu réaliser d'autres missions secondaires non prévues initialement :

Pour faciliter le calcul des impacts associées aux imports de produits finis agricoles en France, un code<sup>15</sup> en langage python a été produit pour extraire des données d'impacts à haute résolution géographique (distinguées par pays) de produits agricoles à partir du logiciel d'ACV OpenLca. Ce code, à permis de fournir une base de données des impacts de produits agricoles spécifiées par pays sous la forme d'un fichier Excel. Au total, environ deux semaines ont été dédiées à cette tâche.

Une seconde mission annexe a été de produire une base de données des impacts unitaires des procédés modélisés à travers le projet ACYVIA (Ademe, [2015](#)), ce travail répond à un potentiel futur besoin de couplage des AFM des filières de transformation animale avec les données ACV, En effet les flux des filières de viandes bovines, porcines, et volailles ont déjà été quantifiés par Terriflux, ces filières à l'exception de la volaille ont été étudiées au sein du projet ACYVIA.

---

<sup>14</sup> Inventaires de cycle de vie

<sup>15</sup> Le code permet également de faire des calculs d'ACV séquentiels, ce que le logiciel OpenLca ne permet pas.

### Planning du stage

Période / Tâches	Février	Mars	Avril	Mai	Juin	Juillet
Prise en main des AFM						
Bibliographie						
Réalisation du couplage pour la filière blé tendre						
Réalisation du couplage pour la filière Avoine						
Réalisation du couplage pour la filière Mais						
Production du script python d'extraction automatisée d'impacts						
Production de la base de données d'impacts non allouées des procédés modélisés sous le projet ACYVIA						
Rédaction du rapport de stage						
Vérification des calculs réalisés /Analyse de sensibilité						



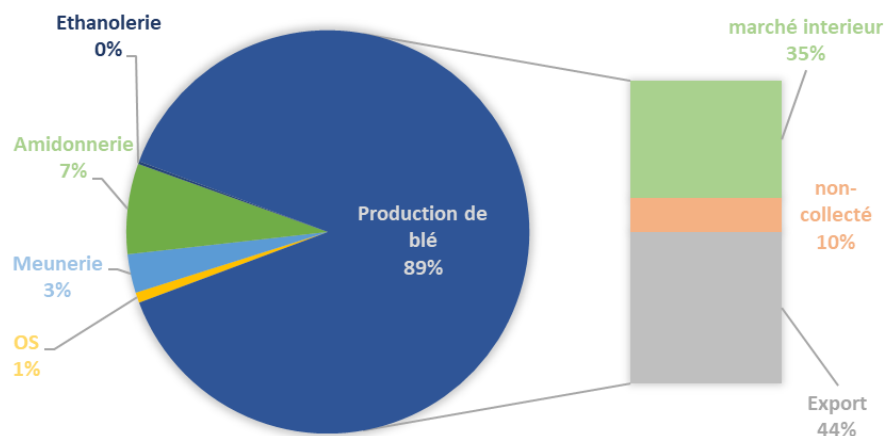
## Résultats

Pour rappel, 4 filières ont été étudiées (blé tendre, Mais, Avoine, Lait), les 3 filières de céréales ont comme pour année de référence 2015, la filière laitière se base sur l'année 2010 pour les flux de matières. 5 indicateurs d'impacts ont été calculés, basés sur deux types de dommages, la santé des écosystèmes (acidification de l'eau et du sol, l'eutrophisation de l'eau douce) et la santé humaine (toxicité humaine cancer/non cancer), le changement climatique est un impact dans le dommage est transversal aux deux catégories.

### Au niveau national

De façon générale, les impacts des différentes filières sont fortement corrélés aux volumes produits à l'exception de la filière laitière pour les émissions de gaz à effet de serre dues aux émissions de méthane des cheptels. Les impacts de l'approche consommation ont été systématiquement inférieurs à l'approche production pour les filières dont les différentes approches ont été calculées (Blé tendre, Mais, Avoine). Cela s'explique par le fait que la France était exportatrice nette en 2015 pour ces types de produits.

**En termes de contribution** les résultats sont concordants avec la littérature scientifique (Poore et Nemcek . [2018](#)), l'étape de production est la première contributrice d'impacts sur les 5 indicateurs calculées pour toutes les filières étudiées, avec selon les indicateurs une contribution de 82% (changement climatique) à 98% (toxicité humaine) des impacts totaux des filières. Pour la filière blé tendre une partie significative des impacts sont liés aux exports, ci-dessous la répartition de l'impact d'eutrophisation des eaux douces par secteur et par destination (des grains produits).

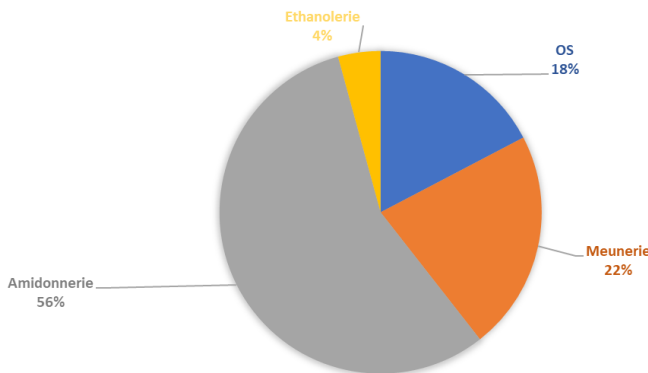


### Analyse de contribution aux impacts CC de la filière Blé tendre par secteur et destination du blé

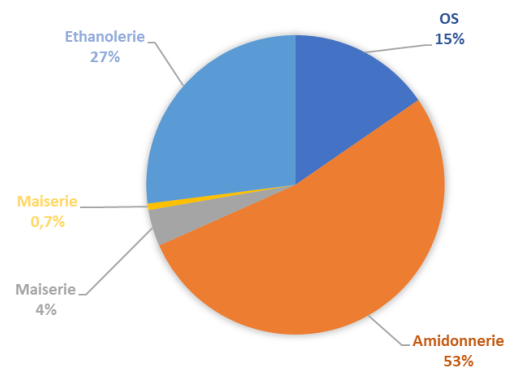
Ainsi près de la moitié (44%) de l'impact eutrophisation de la culture de blé tendre en France est générée afin de satisfaire la consommation finale d'autres pays. Cette pression est relativement locale, car l'eutrophisation (comme l'acidification) est causée par l'excès de l'application de fertilisants dans le sol, fertilisants phosphorés pour l'eutrophisation et azotés pour l'acidification<sup>16</sup>. L'acceptabilité de la génération d'une pression supplémentaire sur les sols d'un territoire pour une finalité non-alimentaire est à évaluer au regard des gains économiques générés par l'activité exportatrice. Au-delà, cette pression additionnelle doit être jaugée au regard de la capacité de charge du territoire, d'où la nécessité de transitionner à une approche absolue en évaluation environnementale (Bjorn et al. [2021](#)), prenant en considération les seuils écologiques soutenables (Rocksorm et al. [2015](#)).

<sup>16</sup> Due à la déposition de gaz ammoniac après épandage des fertilisants azotés

Ce qui est, peut-être, également intéressant comme résultat est la répartition des impacts de l'étape de transformation sur les différents secteurs. (OS désigne le stockage long terme en silos et le transport en amont)



**Contribution des secteurs transformateurs à l'impact CC de la transformation de la filière Blé tendre**

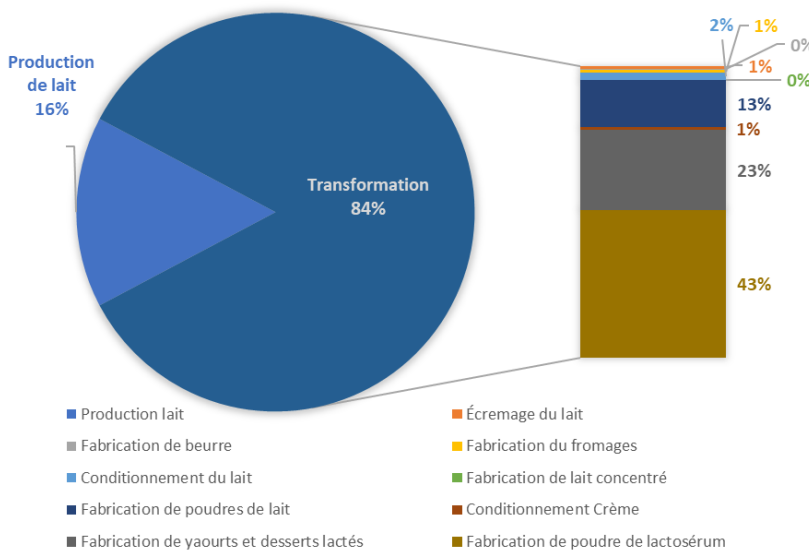


**Contribution des secteurs transformateurs à l'impact CC de la transformation de la filière Maïs**

Pour l'indicateur du changement climatique, sur les deux filières Maïs et blé tendre, l'amidonnerie est le secteur le plus émetteur de gaz à effet de serre. Cela est dû à la forte intensité énergétique du secteur, qui nécessite de grande quantité de chaleur pour l'étape de séchage/concentration<sup>17</sup>. Selon les données ACV, cette chaleur est principalement fournie par des énergies fossiles (gaz en particulier).

### Au niveau régional

Pour la filière lait régionalisée, contrairement au niveau national, la prépondérance de l'étape de production dans la contribution aux impacts n'est plus systématique. Certaines régions comme l'île de France ont une structure de contribution totalement inversée, avec la domination de l'étape de transformation dans les impacts, cela témoigne d'une spécialisation régionale de la filière laitière au niveau de la chaîne de production.



### Transferts d'impacts :

87% des impacts dus à la consommation finale de produits laitiers en IDF sont externalisés hors-territoire, cela s'explique essentiellement par la part élevée des imports dans la consommation finale de la région (82% du lait conditionnée consommé). A l'inverse pour un une région exportatrice nette de produits laitiers comme la Bretagne, 27% des impacts de sa consommation finale de produits laitiers est transféré hors-territoire, principalement le Brésil, pour la culture et la transformation de soja importé. En excluant le transfert d'impacts dû aux intrants, la région

### Analyse de contribution aux impacts CC de la filière laitière en IDF

serait en situation d'internalisation d'impacts de la consommation finale d'autres territoires.

<sup>17</sup> Schéma du procédé = [lien](#)

## Analyse de sensibilité

### Par rapport à la méthode d'impacts

Malgré une certaine maturité de nos connaissances sur l'activité des gaz à effet de serre non-carboniques, des incertitudes subsistent toujours sur l'étendue de leurs effets sur le climat. Pour évaluer l'influence de ces incertitudes sur les résultats d'impacts des filières, j'ai analysé la sensibilité des résultats à la méthode d'impacts, en actualisant les facteurs de caractérisations avec la dernière méthode d'impacts issue du dernier rapport du GIEC 2021 AR6 (IPCC, Foster et al. [2021](#)).

Filières	GWP 100 impacts EF 2.0	GWP 100 impacts GIEC 2021 AR6	Différence en %
<b>Blé tendre</b>	14.1 Mt co2 eq	13.1 Mt Co2 eq	<b>-7.09%</b>
<b>Mais</b>	5.11 Mt Co2 eq	4.70 Mt Co2 eq	<b>-8.02%</b>
<b>Lait</b>	35.05 Mt co2 eq	30.58 Mt co2 eq	<b>-12.75%</b>

### Analyse de sensibilité des impacts CC des filières par rapport à la méthode d'impacts

Globalement, l'actualisation des facteurs de caractérisation a fait baisser les résultats des impacts des filières, cela s'explique par la baisse des valeurs de pouvoir de réchauffement global du méthane et du protoxyde d'azote dans les dernières estimations du GIEC, qui est due principalement à une meilleure compréhension de leur durée de vie dans l'atmosphère et à l'intégration de leur effets indirects par la communauté scientifique. Cette baisse est significative (13%) pour la filière laitière dont le méthane est le principal gaz à effet de serre. En raison de ces incertitudes, la contribution de l'agriculture au changement climatique pourrait potentiellement être sous-estimé<sup>18</sup>.

### Par rapport à la variation du coefficient de rendement des méthodes

Les méthodes ACV et AFM se distinguent par des approches de collecte de données diamétralement opposées, l'ACV peut être classé comme approche « bottom-up », les données sont directement collectées du terrain, alors que l'AFM se base sur des statistiques nationales parfois incomplètes pour reconstituer les flux des filières, elle passe de fait par une approche « top-down ». Ces différences d'approches mènent inévitablement à des différences de modélisations des procédés industriels, même pour des procédés simples comme la meunerie. Comme précisé plus tôt, le coefficient de rendement est l'un des facteurs de l'allocation d'impacts, j'ai ainsi analysé l'importance de sa variation due au modèle utilisé sur les résultats d'impacts des produits/co-produits en prenant comme exemple le procédé de meunerie de la filière blé tendre.

Flux sortants	Variation des impacts en %	Coefficient de rendement
<b>Farine modèle AFM</b>	<b>1.02%</b>	0.784
<b>Farine modèle ACV</b>		0.776
<b>Issues modèle AFM</b>	<b>3.24%</b>	0.216
<b>Issues modèle ACV</b>		0.224

### Analyse de sensibilité des résultats d'impacts unitaires aux coefficients de rendements des modèles AFM/ACV

En conclusion, les résultats d'impacts des produits varient de façon linéaire avec la variation relative de leur coefficient de rendement, pour une même variation de rendement absolue (0.08), le produit/co-produit qui représente la plus faible part de la production verra ses impacts varier le plus significativement.

<sup>18</sup> L'incertitude du PRG du méthane et protoxyde d'azote est d'environ 40-45% (IPCC, Foster et al. [2021](#), Chap7. p95)

Cela peut s'avérer problématique dans le cas où le flux sortant minoritaire (en termes de volume) est le produit principal (le cas de la fromagerie). Par conséquent le coefficient de rendement est un paramètre important dans les résultats d'ACV de produits agricoles issues de procédés multi-output.

## Limites et perspectives

### ***Le besoin d'une approche conséquentielle en ACV***

L'Analyse de cycle de vie se distingue en deux approches : attributionnelle et conséquentielle. La première à une finalité descriptive, comme son nom l'indique elle permet d'attribuer une charge environnementale à un système en ne considérant que les flux transitant par le système étudié (Weidema, [2003](#)). De l'autre côté l'approche conséquentielle permet d'évaluer l'impact environnementale d'une décision, en intégrant tous les systèmes affectés par ladite décision. Le stage s'est basé sur une approche attributionnelle qui est la plus répandue et avec laquelle les données d'Agribalyse ont été modélisés. Suivant les recommandations du document de référence ILCD handbook (European commission, [2010](#)), ce qui permet d'orienter le choix parmi les deux approches est le contexte d'aide à la décision, si la décision a des conséquences à l'échelle Macro, c'est l'approche conséquentielle qui doit être retenue. Le sujet du stage se situe clairement dans un contexte d'aide à la décision à conséquences macro à destination de politiques/citoyens, ainsi l'approche conséquentielle doit être utilisée dans la modélisation environnementale à finalité d'aide à la décision. J'ai essayé de modéliser des scénarios alternatifs (en augmentant la part de la production bio), mais cet essai, ne prenant pas en compte les dynamiques du marché (substitution de produits) ni les externalités négatives (usage des sols) à une valeur nulle pour l'aide à la décision.

### ***La faiblesse des indicateurs de transferts d'impacts***

Les indicateurs de transferts d'impacts proposés, ne sont pas suffisamment matures pour modéliser avec précision les transferts d'impacts entre territoires, compte tenu du manque de données d'ICV spatialisées dans les bases de données conventionnelles. Par conséquent ces indicateurs ne doivent être utilisés qu'à titre illustratif. De plus d'autres approches comme les analyses input-output étendue (EE-MRIO), (Muller et al., [2019](#)) sont plus adaptées pour les transferts d'impacts au niveau des pays.

### *Perspectives*

#### ***Une meilleure intégration logicielle***

A l'avenir une meilleure intégration logicielle entre les deux méthodes facilitera grandement les calculs en automatisant des tâches répétitives, en outre cela permettra une amélioration itérative des modèles AFM (compte tenu du fait les ACV sont généralement plus précis), des outils comme brightway (Mutel, [2017](#)) faciliteront l'intégration technique.

#### ***Extension vers de nouvelles filières***

Il serait intéressant d'étendre la méthode à d'autres filières comme la filière de la betterave à sucre qui inclue de nombreux procédés multi-output.

#### ***Transition vers un paradigme de soutenabilité absolue***

Au vu de l'urgence écologique, il est impératif de changer de paradigme dans l'évaluation de la soutenabilité, pour passer d'une évaluation relative et comparative (ce qui est mieux) à une évaluation absolue (ce qui est suffisamment soutenable) (Bjorn et al. [2021](#)). Cette approche a été testée sur l'indicateur d'eutrophisation de la culture blé tendre, avec des résultats indiquant que cette culture consomme une grande part (74%) du « budget » alloué à la France pour ce type de pression environnementale (voir page 52 pour plus de détails).

Pour une liste plus exhaustive des limites et perspectives du stage, se référer aux pages 50-53.

## Conclusion

Les travaux réalisés au cours du stage ont permis de mettre en lumière les difficultés méthodologiques du couplage de l'ACV et de l'AFM. Une bonne partie de ce travail d'harmonisation méthodologique pourrait être facilité voire évité, par une meilleure construction des bases de données ACV, en effet les données « procédés » reconstituées pouvait être incluses dans les bases de données initiales, c'est le cas de la base Ecoinvent qui propose des versions « Unallocated » de ses données. Néanmoins, la complexité des données issues du projet ACYVIA est due notamment à un suivi plus rigoureux des recommandations méthodologiques concernant les règles d'allocations par la standardisation ISO<sup>19</sup>, par conséquent l'hierarchie des règles d'allocations telle que définie dans la norme ISO 14040 (2006a) réduit l'interopérabilité des données avec d'autres méthodes et complexifie le processus de couplage. Cela n'est pas étonnant compte tenu du fait que l'interopérabilité de la méthode ACV ne figure pas parmi les objectifs des normes et guides de références en la matière. En ce qui concerne les résultats en termes d'impacts des filières agricoles, le stage amène peu de valeur ajoutée à ce sujet, il existe déjà une littérature exhaustive et complète dont les résultats du stage se rapprochent en termes d'ordre de grandeurs. Pour les transferts d'impacts Courtonne (2016) a déjà proposé une méthodologie plus complète. En revanche, ces 6 mois ont été une expérience très enrichissante tant au niveau personnel que professionnel, j'ai pu expérimenter ce qu'était la recherche publique, dans une équipe très engagée avec des chercheurs pleins d'humilité qui essaient de donner du sens à leurs travaux au sein d'une institution qui est déconnecté des enjeux environnementaux et sociaux. Cette expérience m'a permis de mieux comprendre la forte interdépendance entre la modélisation et la programmation informatique, mon manque de compétences à ce niveau m'a clairement limité au cours du stage. En termes de compétences, j'ai pu fortement améliorer mes compétences en Analyse de cycle de vie, j'ai pu faire un premier pas dans la programmation et affiner ma capacité d'analyse et de synthèse. Enfin, cette période m'a permis de mieux affiner mon projet professionnel.

---

<sup>19</sup> La norme recommande en première stratégie de diviser le processus multi-output en sous-processus distincts imputables à un seul flux sortant (par ex. créer un sous-process « emballage » pour la farine emballée, sous-processus allouée uniquement au flux sortant qui lui est dédié, évitant la procédure d'allocation), cette règle implique la création de données spécifiques à chaque flux sortant, car ils ne partagent pas les mêmes intrants.

## Introduction:

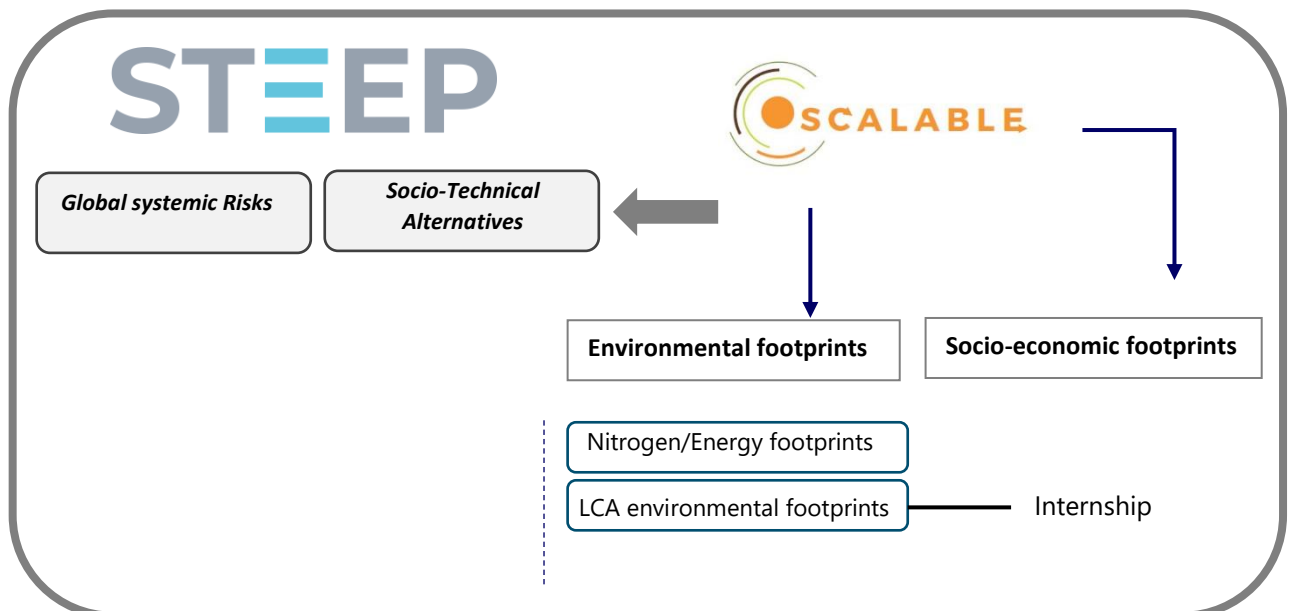
### Context

In the western world, the three decades following the end of the second world war were a short but vivid time of prosperity and carefree living, everything was growing, the population, the economy, the cities. Growth was viewed (even today) as a great measure of the core thêmata (Moscovici, S., & Vignaux, G. 1994) of good/bad, more of it was socially perceived as good, the lack of it as bad. This period ended abruptly in the mid-70's with the oil crisis of 1973, binding the oil supply worldwide and challenging a steady growth.

5 years before the oil crisis, the club of Rome was founded by an Italian industrialist Aurelio Peccei and alexander king a Scottish scientist, gathering hundreds of members, mainly government representatives from OECD. The purpose was to "tackle the problems of mankind like environmental deterioration, poverty, endemic ill health etc., in a systemic way, by developing an "initial, coarse-grain, 'model' or models of this dynamic situation in the expectation that such models will reveal both those systemic components that are most critical and those interactions that are most generally dangerous for the future." (The Predicament of Mankind, the club of Rome, 1970). This was the first robust critique of the Western growth-based development model, which revealed the interconnection between the economy and the environment. It has become urgent to reconsider our societal organisation, in view of the overstepping of the planetary limits of the deregulation of bio-geophysical cycles (Rockstom. 2015), which brought us the climatic stability that has allowed us to flourish as a specie.

### Internship environment:

This internship was held in the STA axis of the STEEP team.



**Figure 1** the context of the internship

STEEP (Sustainability, Transition, Environment, biophysical Economics and local Policies) is an interdisciplinary research team dedicated to systemic modelling and simulation of the interactions between environmental, economic and social factors. The aim is to better understand the biophysical trajectories and sociotechnical alternatives of our societies.

The team is divided into two research axes:



**The GSR (Global systemic Risks) axis**, aiming at modelling systemic risks threatening the sustainability of our society in the long-term and short-term.

**The STA (Socio-technical alternatives) axis**, aiming at modelling the bio-physical dimension of our economy and systemic analysis of alternatives paths.

### –STA: systemic sustainability through bio-physical Economy

Since its first development back into late 19<sup>th</sup> century<sup>20</sup>, the mainstream neoclassical approach of economy has largely ignored natural resources in their models, the most prominent example is the production function, one of the pillars equations of the neoclassical school aimed at maximizing the economic output by optimizing production factors (inputs of the equation), those factors of production were usually labour (L) and capital (K). Neither non-renewable dimension of natural resources nor laws of thermodynamics were taken into account. The 1970s saw the emergence of the question of the finiteness of natural resources with the publication of the report "the limits to growth", which was followed a few years later by the oil crisis, both of which had a strong impact on the economics research community. In response to the threat of an economic growth limited by physical constraints, some economists have even argued that the supply of natural resources could be 'infinite' (Simon. J, [1981](#)).

Fortunately, the economics field possesses a strong diversity of approaches, one of the first attempts to include the finitude of natural resources was the work of Nicholas Georgescu-Roegen in "The entropy law and the economic process" (1971), in which he developed a new economics framework addressing the material and energetic dimension of economic exchanges, the book further emphasised the physical basis of economics with thermodynamics laws, in the sense that men cannot create or destroy matter or energy but just "transform it."

This alternative approach is called, "ecological economics" and is at the main research framework of the STA "Sociotechnical alternatives" axis of the STEEP research team.

---

<sup>20</sup> The transition from classic economy to neo-classic economy occurred in the late 19<sup>th</sup> century with the "marginal revolution", an important debate in the economic sphere on the relative importance of marginality in face of utility theory.

### The big picture of STA:

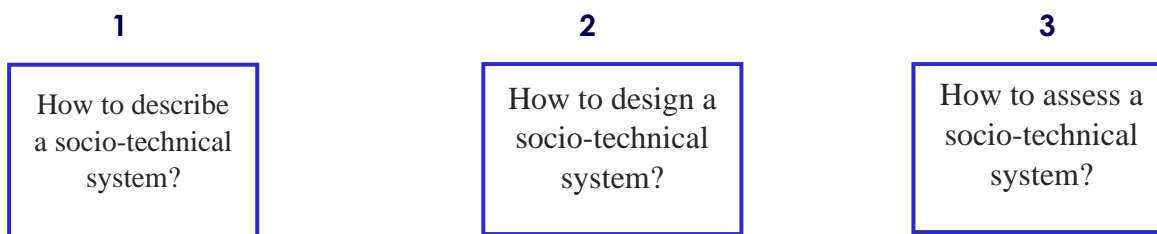
In hindsight the main goal of the STA axis is to: “provide citizens and decision makers embedded in a territory a set of decision support tools to help them assess and choose between a set of socio-technical alternatives about their territory”.

A socio-technical alternative is a coherent arrangement of production and consumption modes embedded in a socio, political and territorial context. It thus involves both technical and social dimensions.

In order to decide between different options, e.g., regarding energy production, one has to look to their potential direct and indirect impacts on social and technical aspects. For instance, the decision to set up bio-gas plants within a territory might have a systemic impact on:

Technical	social
Energy supply of the territory, the use of farm wastes (Manure...), Land use.	The economic model of the farmers (change in revenues, change in the function of the farms...)

Based on this ambitious goal the work of the STA axis is divided in 3 steps:



These 3 steps are carried out using both an **analytical approach** (e.g., in the lab, based on models...) and a **participative approach**, that is, relying on territorial stakeholders to describe what matters to them, identify what should change, design alternatives and deliberate.

The work pursued within the internship is set to help answer the step 3 question “How to assess a socio-technical system?”

Before going forward, let us define the term “socio-technical system”. The concept is derived from systems theory, that covers the interdisciplinary study of systems. One of the most important properties of a system is that it is more than the sum of its parts (Bertalanffy, 1969), and those parts are strongly interconnected. The systems theory is thus the study of those “wholes”, and their properties. A socio-technical system is “the tangible elements needed for fulfil societal functions” (Geels, 2005). In this definition given by Geels and based on the sociology of technology we can distinguish two elements ‘the tangible elements’ refers to the tools and techniques, that are necessary for “fulfilling societal functions” aka social needs. So, we can conclude that a socio-technical system is a combination of techniques and social needs.



## Scalable: Territory vulnerabilities in face of globalised agri-food chains

Scalable<sup>21</sup> is a research project started in 2021 gathering two research centres: INRIA (Institut national de recherche en informatique et automatique), INRAE and local partners (AURA-EE, Grenoble Alpes métropole, TerriFlux) of the Auvergne Rhône-Alpes region.

It aims at analysing to what extent territories are vulnerable with regard to their agri-food chains. To do so, it relies on the analysis of their metabolism. In particular, arising issue of the lengthening of physical (geographical) and socio-economical links within agri-food chains.

**The objective** is to first, analyse the socio-metabolism of agri-food systems, describe their physical flows (material and energy) and socio-economic flows (revenue, employment). Second, based on this metabolism knowledge, assess the vulnerability of territories regarding the metabolism of their agri-food systems. The primary definition of metabolism comes from the biological sciences and refers to the biochemical reactions that enable life within living beings. The concept was extended to ecological economics with the term “socio-metabolism” (Molina & Toledo, [2014](#)), which represents the material and energy fluxes flowing between nature and society, this concept is one of the pillars of ecological economics, explicitly emphasising the dependency of human activity (and thus economical activities) on nature. The term “metabolism” used refers here to the flows of materials and energy that sustain the production and the processing of biomass from agriculture origins.

For the concept “vulnerability”, Füssel, (2007), noted the difficulty to have a consensual conceptual framework as many scholars from different fields (geography, public policies, climate change...) use the concept with own definition based on own field views. We will retain the broad and ordinary definition of Turner and al, (2003) which is the capacity of a system to be wounded. Vulnerability is often distinguished between socio-economic factors and bio-physical factors.

In Scalable, territorial vulnerability induced by embedded Food supply chains is measured in two dimensions:

### Socio-economical footprint

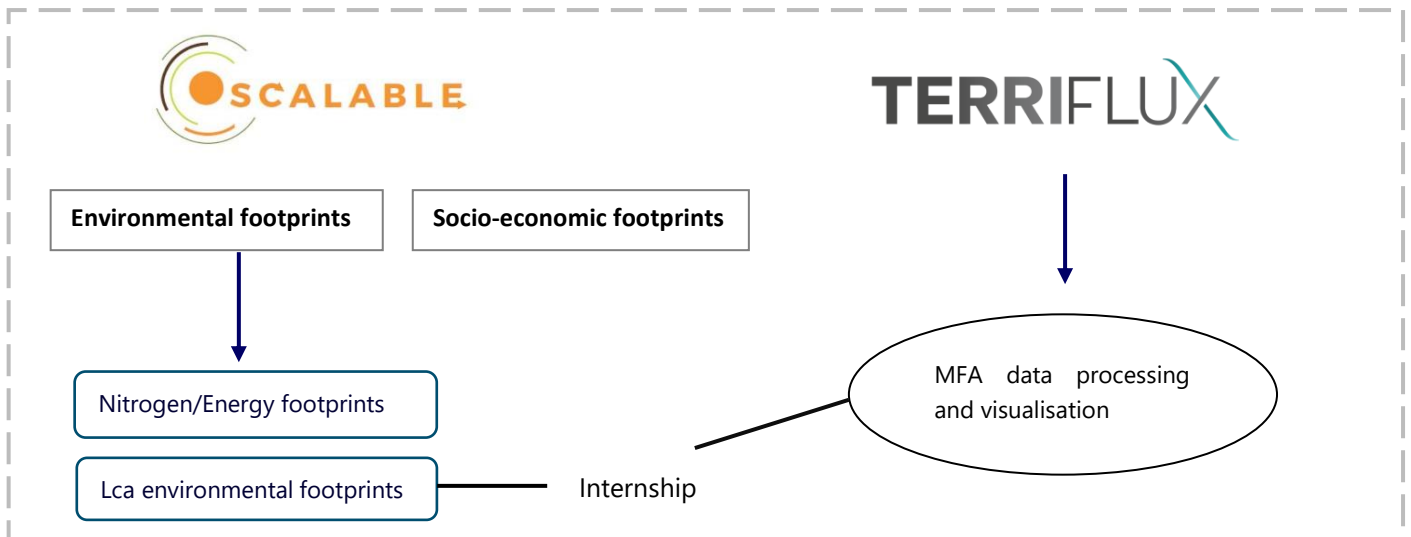
How much of the socio-economical flows (revenues, employment) of the AFS is embedded in the territory?

### Environmental footprint

What are the environmental pressures occurring within the territory?

How much of the environmental footprint of the AFS is outside the territory?

<sup>21</sup> <https://www.projet-scalable.fr/le-projet/>



**Figure 2 :** the contribution of the work to scalable project

Two types of environmental footprints were considered in the project, the Nitrogen and energy footprints, based on the work of Harchaoui.S (2015) and Lca-based environmental footprints. The first approach focuses on the impacts of Nitrogen and energy flows in an absolute sense (nitrogen emissions and depletion, fossil energy depletion) and analyse how better energy and nitrogen flows circularity in Food supply chains could contribute to lower their environmental impacts. The latter uses life cycle assessment data to compute the environmental footprint of a food supply chain and measure the contribution of each stage (production-transport-Processing) and sector (the specialised economic sector that process the raw agricultural material into a consumer product) in the whole footprint. The purpose is to help identify environmental hotspots through the whole supply chain from the producer to the consumer.

### AF filières and Boat: the parents of Scalable

The Scalable project is heavily based on the results of the AF-filières project conducted between 2017 and 2019, its aim was to help decision makers improve their knowledge on the structure of the biomass-sectors flows within their territory (mainly France and French region) for better bioeconomy policies. The project focused on the wood sector and agri-food systems. The main results of the project are data visualisation tools in the form of Sankey Diagrams<sup>22</sup> (appendix 1). On the other hand, the BOAT project focused more on management and valorisation of agricultural Biomass at territorial (infra-regional) scales with a coupled quantitative and qualitative (i.e. based on human sciences) approach. This led to the development of an information system (called SI-BOAT) which centralizes biophysical and socio-economic datasets linked to the production and transformation of agricultural biomass. SI-BOAT can be used to get a quick overview of the main components of the upstream agri-food chain of a specific territory.

### Terriflux:

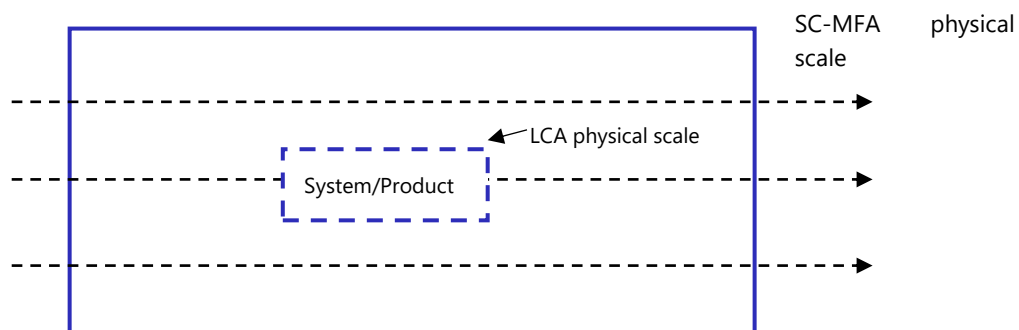
Terriflux is an inria start-up founded in 2021 by Julien Alapetite with the aim of disseminating the metabolism approach to food and non-food biomass supply chains, through data visualisation and treatment (data reconciliation). It provides an open-source web-tool (Open Sankey) to visualize data flows through Sankey diagrams.

<sup>22</sup> [https://www.flux-biomasse.fr/resultats/sankey\\_ble\\_tendre/France](https://www.flux-biomasse.fr/resultats/sankey_ble_tendre/France)

### Research questions:

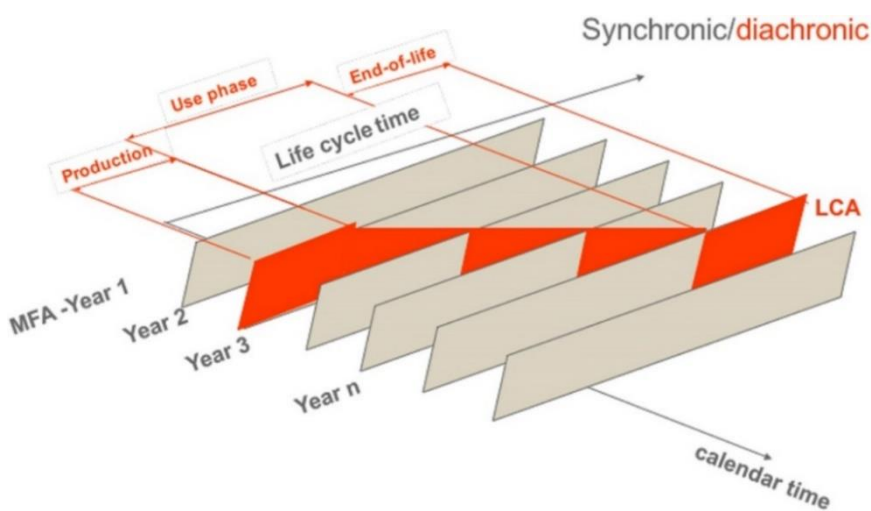
The objective of the internship is to propose a Life Cycle Assessment (LCA)-based methodology to quantify the environmental footprint of a sector (industrial, agri-food, etc.) in a supply chain approach, Food supply chains will be taken as a general case study for this purpose.

One of the main issues to be solved is the mismatch in the modelling approach between Life cycle assessment and Material flow analysis. Indeed, the two approaches deal with time and space in a completely different way (Birat, 2021). First for the physical scale mismatch, LCA was from the beginning designed for product assessment, using concepts from product engineering field (functional unit, life time...), it is thus based on a microscopic scale. On the other hand, Material flow analysis is mostly used in a macroscopic approach dealing with flows covering regions, countries (economy wide approach), cities (urban metabolism), or industrial plants (industrial symbiosis). The system boundary in MFA in its narrowest form covers an industrial plant, where rarely LCA studies go to this level. Figure 3 below describes the physical scale difference:



**Figure 3** Physical scale difference SC-MFA/LCA

Regarding the temporal modelling as presented in figure 3, Material flow analysis is based on a synchronic<sup>23</sup> vision of time, that is it focuses on what is happening for a system in a specific time (usually a year) without considering its past and future evolution. Where LCA takes a diachronic approach, considering the evolution of the reference system expressed in distinguished phases or stages.



**Figure 4** Temporalities in LCA/MFA

**Source:** Birat 2021 MFA vs. LCA, particularly as environment management methods in industry: an opinion.

<sup>23</sup> The term synchronic is defined by the Cambridge dictionary as "relating to something, especially a language, at a particular point in time, without considering how it developed to that point", diachronic is the opposite.

Considering these discrepancies, the main research question is then: **What methodology could be used to build a hybrid footprint model combining MFA and LCA?**

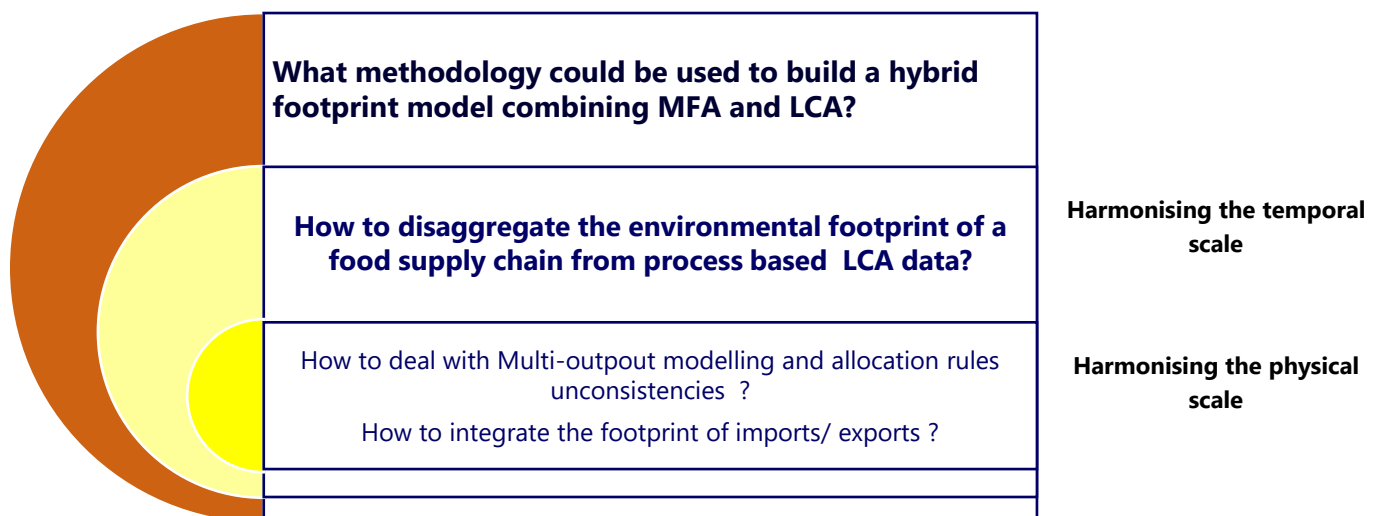
Developing a proposal to this concern would require harmonising the two methods in both perspectives.

**First** in the temporal perspective, indeed LCA data are usually constructed in a full life cycle paradigm (from cradle to grave). Beyond total supply-chain footprint quantification, a need for quantifying separately the impacts of the processing sectors along the chain were explicitly expressed within the research team. This led us to the following sub-question:

Temporal harmonisation **How to disaggregate the environmental footprint of a food supply chain from process based LCA data?**

**Second**, through the internship, we faced a number of inconsistencies between the MFA and LCA models, particularly in the way they model multi-output processes, therefore a harmonisation in the physical modelling is indeed required. The fig 5 below introduces the main research issues that have to be solved.

The research framework proposed in fig 5, is built on a funnel approach increasing in depth and complexity from the general question (up level) to the more technical ones (down level). Overcoming the lower-level issues participate in answering the broad question in the upper level.



**Figure 5** Research framework

## Methodology:

### Life cycle assessment: the core methodology

Life cycle assessment is one of the most widely used environmental assessment method (Nygreen, Antikainen 2010), it is intended to overcome the temporal boundary limit of classic environmental assessment tools by adopting a life cycle thinking approach<sup>24</sup>, broadening the scope of the assessment to the upstream and downstream stages. Thus, including all stages of the life cycle of a system<sup>25</sup> from the extraction of materials to manufacturing, to use phase and finally end of life (disposal, recycling, etc.), figure 6 describe the different scopes used in LCA. Crucially an LCA is a comprehensive method accounting for all direct and indirect emissions that can be assigned to a system through its life cycle.

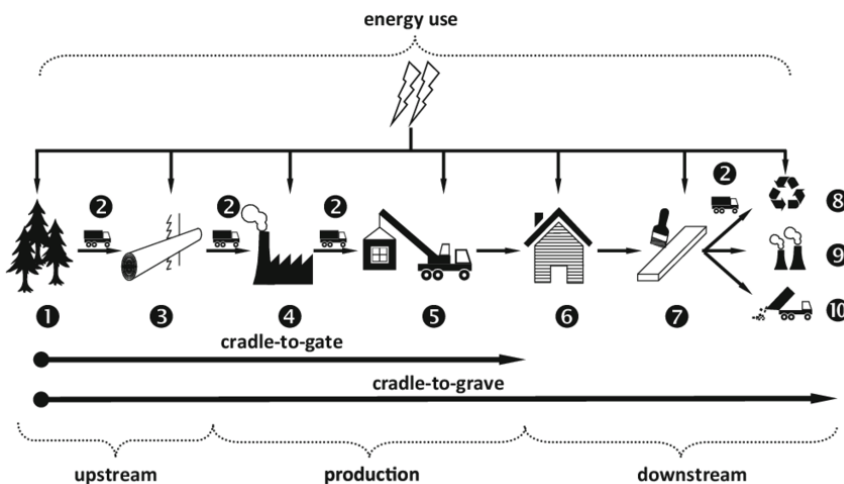


Figure 6 LCA scopes Source: Sandak and al. 2019

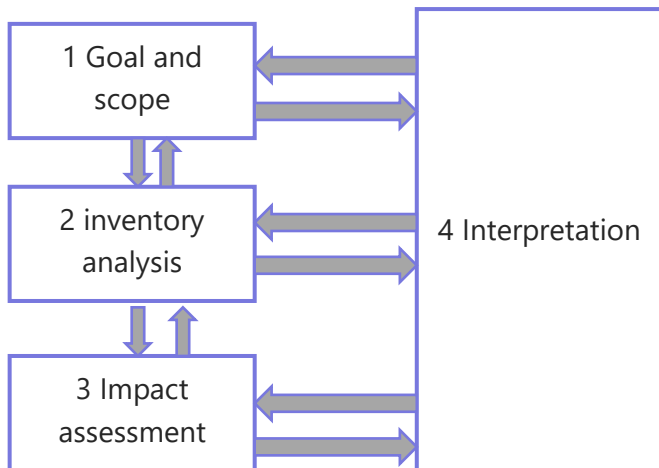
The origins of Life cycle assessment date back to the late 60's when environmental degradations became a topic of concern (Bjørn and al 2018). The first Lca study was conducted by Coca-Cola in 1969, in the following years Lca studies were focused on energy and Greenhouse emissions, and were mostly assessing packaging products. No Consensual method or standard were available at that time, companies were developing their own lca methods based on their needs. it was during the 1990s that the basis of the method was developed and formalised, the publication of the ISO (international organisation for standardisation) Lca standards (2006a,2006b) in 1997 pushed greatly the methodological development and the interest of both academics and companies for it, suddenly LCA gained international recognition. The method has well matured in the last two decades to become a reliable sustainability assessment tool.

Following the international standardisation (ISO 14040, 2006a), an LCA study have four main phases:

**I-Goal and scope definition:** The first step in any LCA study is to define the objectives and the scope of the study, since the tool is primarily intended to support decision-making. The goal is defined in close collaboration with the decision-makers. The scope describes what will be considered or excluded in terms of life stages (diachronic scope) and potentially system sub-components (physical scope). To enable comparability of the results a functional unit must be defined, the ISO14040 standard describe it as "quantified performance of a product system for use as a reference unit".

<sup>24</sup> United Nations Environment Programme., & Life cycle initiative. (2013). *Greening the Economy Through Life Cycle Thinking* (p. 60). [Report link](#)

<sup>25</sup> The term "system" used here refer to both products and production systems (energy production...) as well as organisations.



**Figure 7** The four phases of an LCA study based on ISO 14040

**II-Inventory analysis:** This second stage is usually considered as the most time-consuming (Bjørn, A. et al. [2017](#)) it consists of the quantification of all the relevant inputs and outputs of the system through its life cycle. The ISO standards splits this step into three stages: 1) data collection where all the data related to the system are gathered and classified (energy, raw materials, outputs.), 2) data calculation including the following procedures "validation of data collected, – the relating of data to unit processes, and – the relating of data to the reference flow of the functional unit" (Iso 14040, [2006a](#)) 3) allocation of flow and releases in case of multiple outputs and recycling.

**III-Impact assessment:** after quantifying the system's emissions, these emissions must be translated into impacts through the characterisation phase, which consists of transforming raw emissions into impacts. The characterization models are what distinguishes the impact assessment methods.

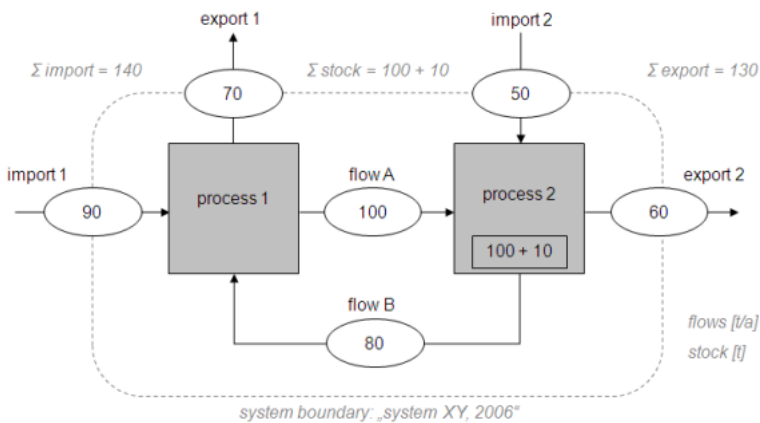
**IV-Interpretation:** This is the final phase where the results of the study are analysed in the light of the uncertainties and assumptions made earlier. Typically, a contribution analysis is performed to identify the processes, elementary flows or life cycle stage that have a strong influence on the final impacts results. Then a sensivity analysis is carried out to evaluate the variability of the results regarding the methodological choices, assumptions and data choices. Both were performed in the internship.

As shown in Fig.6, a lca study is an iterative process where each phase is reviewed and updated as the study progresses.

There are two types of approaches in LCA, attributional and consequential, the first approach aims at giving a picture of the environmental impacts of a system by assigning to it the environmental burdens e.g (emissions) occurring within its boundaries, in other words the attributional approach cuts the world into a small system and assign to it the environmental impacts of its emissions (B.Weidema [2003](#)). In the other hand the consequential approach aims at assessing the environmental impacts of a decision, extending the system boundaries to all the systems affected by the decision. In our case, we will focus on the Attributional approach. more reflections on the consequential approach can be found in the "limits and discussions" section.

## Material flow analysis:

Material flow analysis is a core method in industrial ecology and anthropogenic metabolism (Baccini & Brunner, 2012), aiming at quantifying flows and stocks dynamics within a well-defined system, it's the main method to analyse the bio-physical aspect of an economy. The method is used to analyse a high spectrum of objects and scales ranging from substances flows (chemical elements, e.g copper, nitrogen) to goods flows (products that contains multiple substances), it was further expanded to energy flows. It is based on system thinking with 4 main components (fig 7): the system boundary which frames and bounds the analysis, the flows (matter, substances or energy), the processes that transforms input flows to output flows and the stocks (within processes or separated).



**Figure 8** Simple MFA model source: Stan2web

The definition of a system boundary, allows a wide range of spatial scales for MFA studies, from the plant level (Shahbudin & Kamal, 2021), to the country-level economy-wide MFA (Raupova et al., 2014). Our work is positioned under the supply chain approach of MFA.

## SC-MFA

The concept of supply chain MFA was popularised by Courtonne (2016), this approach gives a hybrid view between the goods MFA and the supply chain viewpoint tracing flows from raw material extraction through the different processing stages to the final consumer. Conceptually the supply chain view shares a lot of similarities with the term commodity chain defined by Talec and bockel (2005) as : "the name given to the succession of operations and of agents which, starting upstream with a raw material, eventually emerge downstream, after several stages of transformation and increases in value, with one or more final products at consumer level. A chain is thus a series of operations (transformations) of agents and of markets, which lead to physical flows and their counterparts in monetary value". in contrast to EW-MFAs, SC-MFA is economic-oriented, where the intention is to inform the various actors in the food production chain of the structure of the raw material and processed products flows rather than improve the environmental performance of the system. Another notable difference is that EW-MFA is based on a strict mass balance rule, where SC-MFA only deals with a specific raw material and its transformed forms, allowing the mass balance to be broken (indeed, other flows like water are not accounted for). The supply chain MFA is based on the dual supply and use tables framework to organize data between producers and consumers. Supply tables refers to the origins of the flows, where the use table refers to their destination.

## Territorial Life cycle Assessment

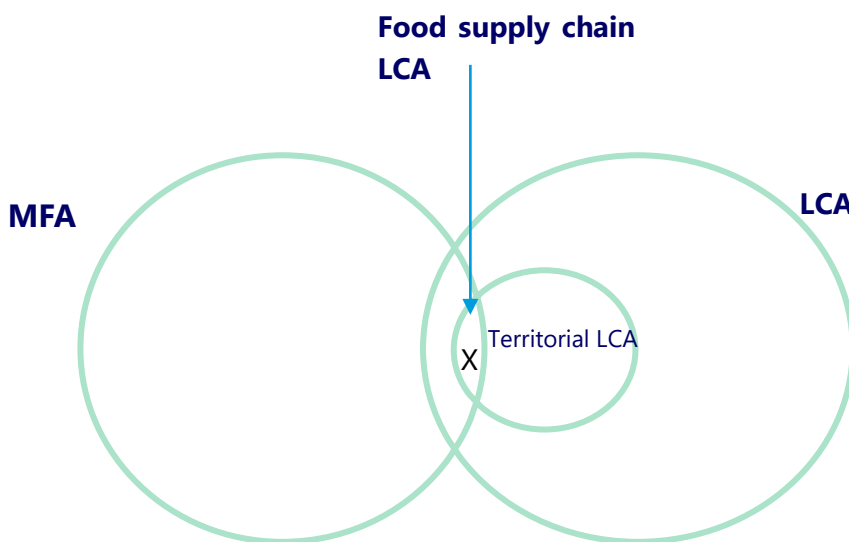
As stated before, Lca is a disaggregated method, developed in a product-oriented approach, making it difficult to implement for macro-systems with large spatial scales. To overcome this limit, Loiseau (2018) proposed an extension of the methodology to territories, a territory is defined in three dimensions, the physical dimension (physical borders), the organisational dimension (the various stakeholders present) and the identity dimension (the perception of its inhabitants of it), hence this systemic definition proposed by Loiseau: "a complex system combining a geographic area, a system of stakeholders and a system of representations". The new approach has been differentiated into two types with regard to the scope of the study:

T-LCA Type A: based on the PhD work of Laurent.F (2015), this approach focuses on a system which is territory contextualized (embedded in a territory), the case study most used to illustrate it is a biogas Plant.

T-LCA Type B: Which refers to an LCA of the whole territory, usually distinguished by consumption and production impacts, (consumption impacts being calculated with input/output analysis).

A food supply chain can hence be classified in the type A, where it is physically embedded in a number of territories through its industrial plants and crop land use, even though it is uncommon to have all the processing sectors in a meso-scale territory (region-level), we can have a territorial view if we restrict the system to the production chain of one product (e.g Butter, Wheat flour), which is more likely to be found in the real world in short food supply chains. Thus, it is possible to conduct a "Territorial" lca of the flour production of a territory including the milling plant and the wheat fields within the region.

In regard of the different methods presented earlier, we set food supply chain lca in the intersection between MFA and LCA and notably territorial LCA. (Fig 9)



**Figure 9** FSC LCA Method integration between LCA and MFA



## The case studies:

Through the internship, 4 Food supply chains were modelled: **Soft Wheat, Maize, Oats, Dairy**.

The MFA data of the cereals food supply chains were based on the study of the Scientific interest group "Avenir Elevage"<sup>26</sup> to quantify the material flows of feedstuff, the final report can be found here [link](#) (in French). As a consequence, the animal feed destination as a recipient of flows has been more precisely modelled. the study was carried out over a period of three years (2017-2020), with 2015 as the reference year for data. For the Dairy food supply chain the data were based on the AF filières project (AF filières. [2017](#)) and the Phd thesis of Michela Bevione (Bevione, [2021](#)) with 2010 as a reference year.

## System boundaries

Below the system boundaries chosen for the study, more details can be found in appendixes for each FSC system.

Type of System boundary	Cereals	Dairy
<b>Value chain</b>	Production and first processing stage, except for oats (only production)	From the production stage to the last processing gate phase including packaging.
<b>Geographical boundary</b>	Only country level (Including imports and exports)	Country and region (international Imports/exports excluded)

**Table 1** System boundaries of the case studies

## LCA Databases used

For food processing and production, Lca Data were gathered from the French Agribalyse 3.0.<sup>27</sup> database, it is considered one of the leading lca data providers for agrifood lca data. For Transports Ecoinvent 3.4 was used and to compute the footprint of the imports, The EF 2.0 ([European C.](#)) database was used, it provides country-specific data on agri-food products. The version used and available online is the output of the pilot phase (2015-2021) of the EU commission project for a unified green market with harmonized LCA methodology, the 3.0 version is under development. All the Lca calculations were performed on OpenLca 1.11.

## Lca impact assessment methods used

The selection of the characterization method can have a strong influence on the results, especially for indicators such as toxicity where there is still a lot of advancements and improvements in the modelling accuracy and resolution (Belyanovskaya et al [2020](#), Dorca-Preda et al [2022](#)), with characterisation factors that can vary greatly with new developments. We tried to use the most up to date impact assessment method, for the cereals case study the EF 2.0 method was used since it's the only impact assessment method consistent with the EF 2.0 database, however this version includes obsolete CF<sup>28</sup> for toxicity impact categories based on the USETOX 1.0 model. As a consequence, to improve the robustness of the results, the toxicity impact categories were updated with the Usetox 2 (recommended + interim) method (Belyanovskaya et al [2020](#)). Regarding the Dairy case study, the EF 3.0 were chosen for calculation.

<sup>26</sup> <https://www.gis-avenir-elevages.org/>

<sup>27</sup> <https://doc.agribalyse.fr/documentation-en/>

<sup>28</sup> Characterisation factors

## Functional unit

The coupling of LCA and MFA make it difficult to choose one functional unit as required in classical LCA studies by the consensual standardisation, since MFA's that are based on supply and use tables (the case for the agrifood systems) focuses on flows that circulates between a supplier system (from which the flow in an output) and a user system (that receives the flows as an input). Hence this dual approach of consumption/production (see fig 7). As a result, depending on the lens of analysis, there are two functional units:

**Production lens:** "All the products provided by a food supply chain in a year"

**Consumption lens:** "All the products within the category of a food supply chain consumed in a year"

## General assumptions and parameters:

This part gives an overview on the shared assumptions taken for all FSC's; a more comprehensive part can be found in appendixes for assumptions specific to each one.

### *Transports:*

This section refers only to the transport of products occurring in exports/imports for the cereals case studies.

**Rail** = We selected the "market for" dataset for freight rail transportation with Europe without Switzerland as location.

**Sea** = The Ecoinvent database offers various sea oceanic ship transport datasets to choose from, mainly distinguished by whether it transports freezed containers or not. For our case studies we assume it is transported in conventional non-freezed containers, we selected the data representative of ships with 50,000 DWT (deadweight tonnage) capacity. This data may not be representative of the average transoceanic ship's capacity, but it was the only data available.

**Road** = For freight road transports, we had to select data based on two main criteria, Trucks capacity and the technology level denoted by the version of the European emissions standard Euro (), we chose the lorry trucks of capacity >32T<sup>29</sup> and compliant with the norm EURO5 representative of the vehicles sold from late 2008<sup>30</sup>. This type of lorries is representative of the French fleet based on the ecological transition ministry data on Heavy (2020 data) vehicles statistics<sup>31</sup> claiming a median age of 3 year. Even though the representativeness with the year of the case studies is not guaranteed, we assume that the median age didn't change since 2015 (for cereals).

**Inland-water** = We selected the "market for" inland water barge dataset.

### *Uncertainty handling*

Fortunately, Uncertainty data were available in the agribalyse database, as the first contributor to impacts is the production phase, we runned monte-carlo simulation at 1000 iterations for all the crop production processes to propagate and integrate uncertainty in the Lca impacts data. The mean impact values of the simulation were then used.

---

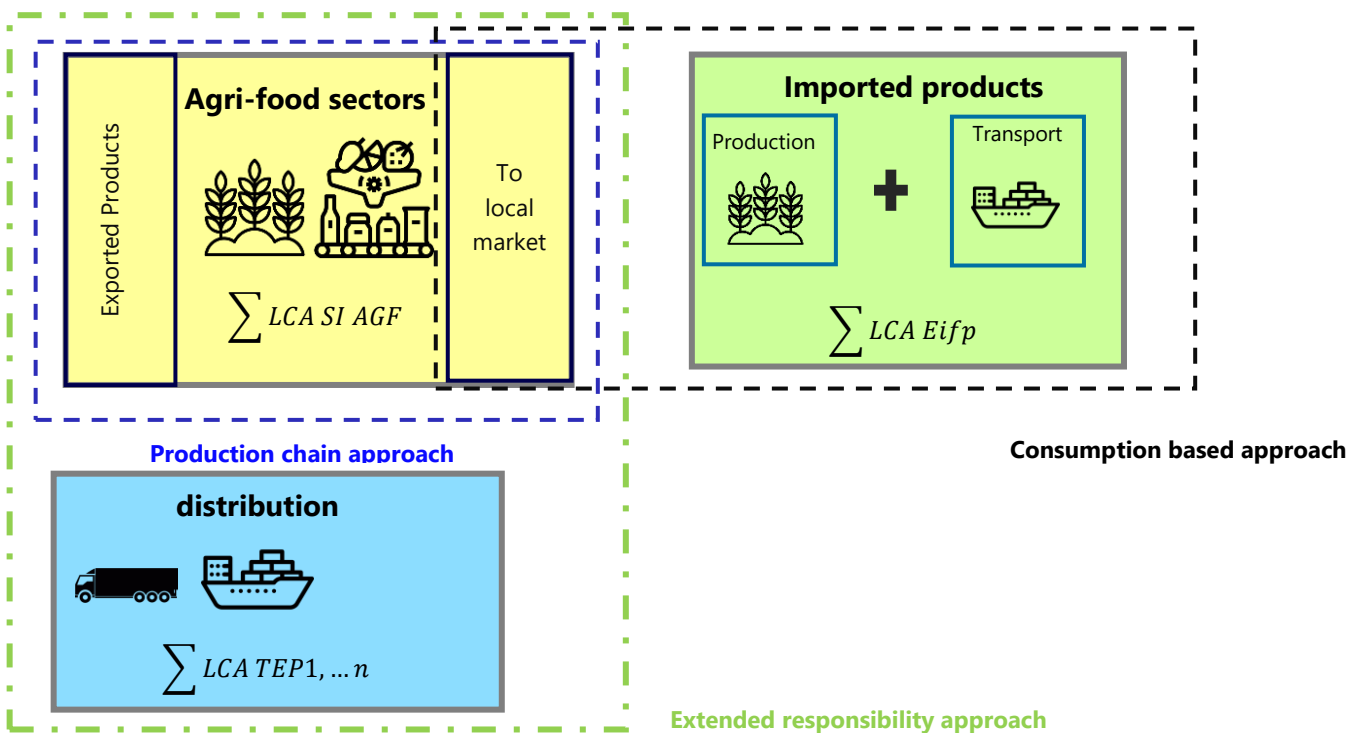
<sup>29</sup> For international trade we assume the freight lorries are of >32T size

<sup>30</sup> <https://dieselnet.com/standards/eu/hd.php>

<sup>31</sup> <https://www.statistiques.developpement-durable.gouv.fr/le-parc-de-poids-lourds-en-circulation-est-stable-au-1er-janvier-2020>

## Coupling MFA and LCA: a proposal for food supply chains

Regarding the literature, combining MFA/LCA was done for two main purposes: assessing the impacts of end-of-life strategies of a specific material ( Nakem et al. [2016](#), Rochat et al. [2013](#)) or assessing the environmental impacts of urban metabolism and its related hotspots (González-García et al. [2019](#), Lavers Westin et al. [2019](#)). This type of coupling can be classified as *soft coupling* where the outputs of a model ( flow values from an MFA) are used as an input to another model ( LCA), in contrast of *hard coupling* where models interact in a closed loop (the input of one will affect the inputs of the other), this classification was based from the work of beaussier ([2020](#)). The framework proposed below is a modular soft coupling approach. Figure 10 graphically explain the framework:



**Figure 10** Framework for quantifying the environmental footprint related to both consumption and production side of an agrifood sector . AGF = agrifood sector, EP = exported products iFP = imported final products. In the dashed frame the downstream responsibility approach.

The coloured full boxes, represent three types of environmental footprints differentiated by the sharing principles of responsibility through the value chain (Weidema et al. [2018](#)), the yellow one describes the environmental footprint of the food production chain including food production, processing, transport, and the environmental impacts of upstream inputs (fertilizers for the production stage, energy and chemicals for the processing stage). The blue box is a system boundary extension of the first one, adding the distribution stage into consideration, the rationale behind is that the producer is responsible (fully or partially) for the impacts of the transport of its products to the client in line with “beneficiary pays” principle this extended system boundary was used by Güereca and colleagues ([2022](#)) for an LCA of agro-industrial systems of sugar in Mexico. The share of the impacts of transports between the consumer and producer is a subjective philosophical question based on value decision. Weidema and colleagues (2018) summarized the three principles of allocation in the value chain (table3) : territorial (based on direct impacts in the territory), Consumption (based on the demand side) and income (based on the supply).

Responsibility principle	Driver	Activity scope	Impacts
Territorial	Activity	Direct	Direct
Consumption	Demand	Direct and upstream	Direct and embodied
Income	Supply	Direct and downstream	Direct and enabled

**Table 1** The three principles for allocating responsibility through the value chain (Weidema et al. 2018)

Our proposed framework, is then consistent with the responsibility principles described above, except for the Territorial principle in which the impacts are restricted to the direct emissions.

Finally the green box encompasses the impacts of imported final products which belong to the same group of the system under study i.e related to the primary raw products (wheat, milk..). It can be used to quantify the environmental impacts related to the consumption of a group of products in a territory (apparent consumption) by summing it with the production impacts minus the impacts of exported products. This final view can be classified as a consumption-based approach (equivalent to the footprint accounting). Furthermore, improvements in the environmental burden linked to the consumption pattern of a product could be investigated through scenario analysis with the geographical origin and importation rate as variables.

The environmental footprint of an Agrifood system is calculated as follow:  $EF_{sector} = \sum SI_{AGF\ sector1} \dots n$

Where *AGF* is an agri-food sector<sup>32</sup>, *SI* the scaled Impacts calculated by multiplying the value of output flows from a sector with a representative LCA of the process of the AGF. .

The environmental footprint of the imported products is calculated as follow:  $EF_{IP} = \sum Eifp$

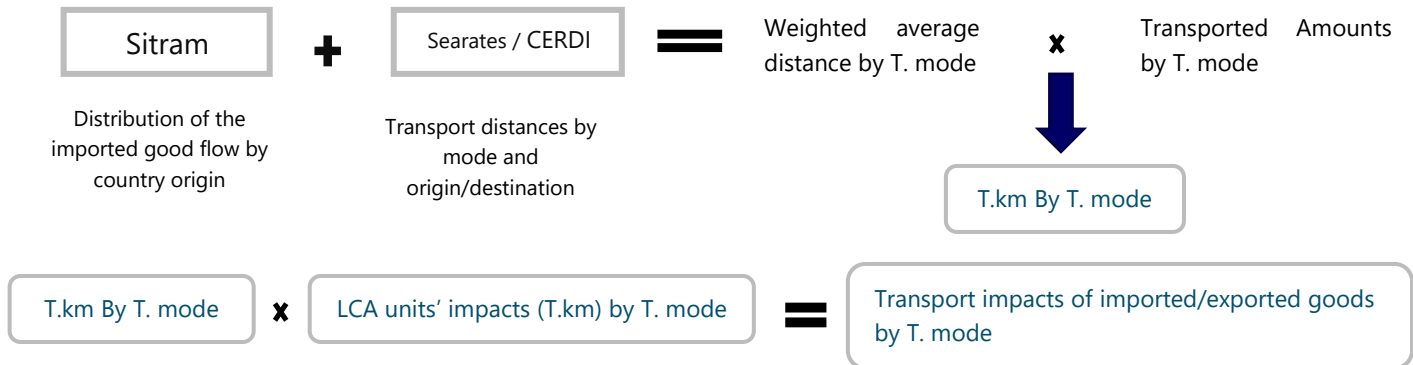
Where *Eif* is the embedded impacts of an imported final product *p* in the system, to calculate the environmental footprint of an imported product, the first step is to get the impacts per unit of the imported products by weighing the impacts by country of origin, international trade databases can be used to get the distribution by country, as an example the Sitram<sup>33</sup> database was used for France, then based on country differentiated lca data (WLFDB or Agrifootprint data are country differentiated), an average weighted lca impacts can be calculated, when country specific data is not available, region specific data could be used. Now that the impacts of the production of an imported flow is computed, the second step is to calculate the impacts related to its transport to the country or region of study, two parameters are required: the distances and transportation type. Data on transportation type of imports products flows were available in Sitram, country distances are available in online databases like searates<sup>34</sup> or CERDI for sea distances (Bertoli et al., 2016), then a consecutive procedure of weighting and multiplication is proceeded, Fig 10 show the different steps for the calculations. The Sitram database offers a low level of details in terms of products classification, usually mixing products into groups (for example gluten, starch and wheat gluten in the same class), we then have to take the assumption that the type of transport is similar within a Sitram class of products and that the differences are trivial.

<sup>32</sup> An agrifood sector is a group of actors processing and using the same inputs and producing the same outputs, within a food supply chain, the milling sector is a great example of it. In the MFA's produced within AF-filières, the term includes the primary agricultural production.

<sup>33</sup> <https://www.statistiques.developpement-durable.gouv.fr/donnees-sur-les-flux-de-marchandises-sitram-annee-2015>

<sup>34</sup> <https://www.searates.com/services/distances-time/>

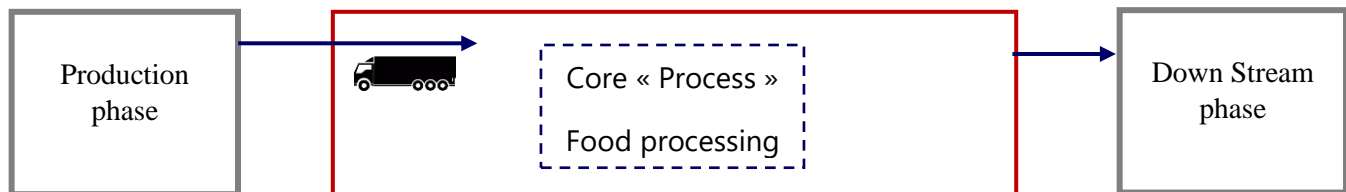
A way of reducing the uncertainty around the typology of transport is to use the European NC8 combined classification for goods flows (The Combined Nomenclature, EC) it is to date the structure with the highest level of details for international and Eu traded products. The information on transport type is normally registered by the customs services of each EU member state. We weren't able to access this data for France



**Figure 11** procedure to calculate the embedded transport impacts of import/exports goods

## The disaggregation question: towards a modular approach

Lca data are usually built in a cradle to grave system boundary, that is including the material extraction phase('cradle'), the production phase, use phase and end of life phase ('grave'). This inventory modelling scope was the one chosen for food lca data in Agribalyse. Using these data for quantifying the environmental footprint of a supply chain would inevitably lead to double counting of the impacts of the production phase, as these impacts are "embedded" in the final product environmental impacts (see figure 6). Consequently, to tackle this issue a data post-treatment is indeed necessary. We solved this issue through switching the initial data from a "cradle-to-grave" system boundary to "farmgate-to-plant gate". The new data scope excluded all the impacts occurring within the farm.



**Figure 12** The farmgate to plant gate scope used, represented in the red frame

Farm gate to plant gate = Cradle to gate LCI – Raw main agricultural input

This enabled us to effectively separate the impacts of each value-added process in the production chain.

The main cause of this, is the cumulative approach in LCA, where the impact of the final product encompasses all the processing steps upstream, in this manner, the climate change impact of 1 kg of wheat flour includes the CC impacts of growing the necessary wheat grains to produce this final product, but above it also includes the CC impacts of the amount of fertiliser that was necessary to grow the amount of cereal.

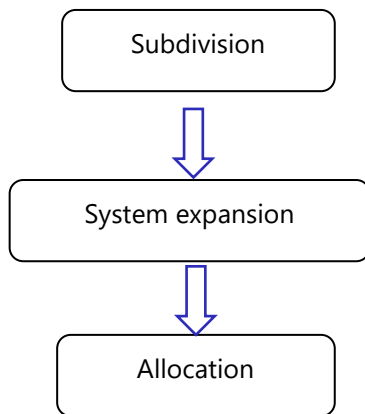
Separating Life cycle stages in food production chain was investigated in the early in LCA development (Jungbluth et al.2000) for decision support at the consumer level. 5 modules were identified, agricultural stage, processing and distribution, Transport, Packaging and finally consumption. The system boundary chosen above, can be understood as a macro module of 'processing' and 'transport to plant' stages. This can either be done through manually duplicating the initial process data without the raw main input or cancelling the connections with the raw main input data at the Product system stage (with open LCA). The latter requires much less time (<20s per product system), and can be used for small simple systems. However, for complex systems like the dairy sector that have multiple processing stages or for extended system boundary studies (from farm to plate approaches). The additional extra work required is not appropriate regarding the time-constraints that exists around LCA studies. Thus, an automation process would be necessary, for this purpose Steubing.B and colleagues (2015)<sup>35</sup> developed a modular LCA approach that can be automated through the Activity browser software. Additional programming skills will be needed.<sup>36</sup>

<sup>35</sup> Steubing, B., Mutel, C., Suter, F., & Hellweg, S. (2016). Streamlining scenario analysis and optimization of key choices in value chains using a modular LCA approach. *The International Journal of Life Cycle Assessment*, 21(4), 510–522.

<sup>36</sup> Importing specific databases like agribalyse 3.0.1 in the brighway2 python framework requires additional data treatment due to data formatting inconsistencies between databases.

## Multi-output modelling harmonisation

Differences in the way LCA and MFA model multifunctional processes was by far the main challenge of the internship, in the LCA community the modelling of multi-output processes is a long-lasting debate that is still actively driven specifically for the agricultural sector (Mackenzie et al. [2017](#), Wilfart et al. [2021](#)), The ISO14044 (2006b) international standard recommends the following hierarchal procedure to deal with multifunctional processes, In three steps :



The ISO standard states « Wherever possible, allocation should be avoided by 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes. »(Iso14044,[2006b](#)), so before allocating the inputs of a process to its different product/co-product flows, one should try to subdivide the unit process into smaller processes that are related and specific to each output flow in the macro-process e.g the sub-process of bagging of flour is specific to bagged flour in the milling production chain. In this respect the inventories for food processing sectors within the ACYVIA<sup>37</sup> project were mostly modelled with subdivision. When separating a process into sub-processes is not possible (physically), it is suggested to expand the system to the new

functions fulfilled by the co-products, adding market variables and related economic assumptions in the model (Product substitution...). Finally, if system expansion is not possible or viable (due to the difficulty of identifying a proper product to be substituted.), allocation based on specific values of the output flows is proposed, this allocation can be based on physical relationships between the products (dry mass, partitioning of energy use..) or indirect relationships (economic values).

In practice allocation by economic values is usually preferred in lca studies, as it is the simplest and less resource-consuming method in multifunctionality handling, data on prices are generally available, where information about the physical relationships of co-products is for example harder to identify, in agri-food lca's, it is the most recommended allocation method<sup>38</sup> regarding the literature (Wilfart et al. [2021](#)).

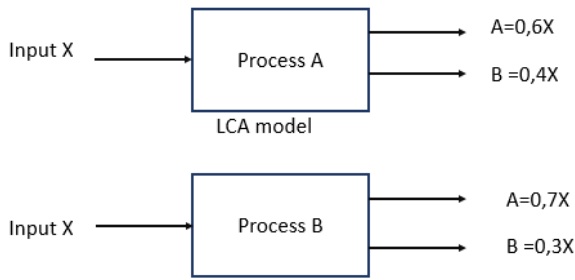
### **The issue:**

At first hand, the most obvious way to compute the environmental impacts of a system with multiple flows would be to simply multiply the Lca impacts per units of flow with flows mass, assuming the flows of the system relates to existing products in classical Lca databases e.g wheat flour, skimmed milk, Butter. This would be perfectly correct in a system with mono-functional processes where the impacts of related to a flow only depends on the functional unit F, assuming the same characterisation factors.

In a multi-functional process, in case the multifunctionality is dealt with allocation, the allocation factor of a product x is then a new parameter added to the equation, binding the impact of the product or co-product to the "share" of the impacts of the process assigned to it. Thus, the extent of the environmental burdens of an individual product/flow in our MFA system would perhaps be binded to the allocation values assumed at the LCA modelling side. Even without considering allocation phase, due to differences in the resolution of co-products modelling, and various co-products classification, the physical distribution between the output flows may vary from nearly the same to more than the double. it turns out that multifunctionality is almost always addressed by a type of allocation, at least in classical attributional lca databases.

<sup>37</sup> ACVYA is the life cycle inventory project that provides the lca data on processed food in Agribalyse.

<sup>38</sup> Versus physical or biophysical allocation



**Figure 13** Differences in multi-output modelling between MFA and LCA

### Example:

let's take a simple example to highlight the consequences of those inconsistencies on the final impacts result. Let's have two processes, Process A, a multifunctional process previously modelled in a LCA study with two output flows A and B, each with a yield factor<sup>39</sup> of 0.6 for the first and 0.4 for the latter. And Process B the same process modelled differently in a Material flow study, where flows A and B have slightly different yield factors (0.7 and 0.3). Let's assume that based on the lca model, one unit of each flow (a unit is

equivalent to X, the unit of the input) have a climate change impact of 200 kg co2 equivalent for flow A and 150 kg co2 eq for flow B.

The global impact of the process A would be 180 kg co2 eq, where it is 185 kg co2 eq for Process B, given the flow unit impacts provided by the lca model. Regarding the amounts of flows considered (millions of tons for cereals), a 2.7% difference in impacts results of a process can have a significant influence on absolute emissions. We have encountered this issue, on the soft wheat FSC with the starch processing sector, below in table 2 the mismatch in output values found in the starch sector:

Output flows	Lca Model	MFA model
Gluten	9.4%	7.2%
Wheat gluten feed	22%	×
Starch	54%	53%
Starch slurry	41.9%	×
Wheat gluten feed + solubles	×	42.9
Wheat bran	17.9%	×

**Table 2** Output flows values mismatch for the starch soft wheat sector, due to moisture change in the process, the sum of the output flows is over 100%

Due to moisture change in the process, mass balance is not met. Beyond numerical differences in the output values, some flows are simply lacking in the MFA model (wheat bran...).

### The harmonisation method:

To harmonise the two models, we propose to move from allocated product-oriented data to non-allocated process data, indeed the mismatch between the two models is mainly on the flows, that requires a high modelling resolution. The Agribalyse database is based on multiple data providers (Ecoinvent for the background data, Agri footprint for imports data, internal LCI projects...), as a consequence the inventory modelling varies significantly depending on the data provider, in fact Agribalyse have set up methodological rules for life cycle inventories projects conducted within (Mainly the ACYVIA<sup>40</sup> project), however this methodological framework doesn't apply for external data providers. For agrifood lca data provided by Agrifootprint, fortunately the database already provides multifunctional Process-oriented data<sup>41</sup>, the multifunctionality were solved through allocation. The inventory wasn't subdivided by flows; thus, it includes all the inputs of the process required for

<sup>39</sup> The amount of the flows output divided by the initial quantity of the input.

<sup>40</sup> Référentiel méthodologique permettant la production de données d'ICV pour la transformation agro-alimentaire. (n.d.). La librairie ADEME. Retrieved 24 June 2022, from [link](#).

<sup>41</sup> For example, the « Wheat gluten feed, gluten meal, bran, starch and starch slurry" Lca process data including all the outputs of the starching process.



all output streams, so in outputs all the flows are considered in the same process (see below in fig 8 for the Starch process).

Inputs				Outputs			
Flow	Category	Amount	Unit	Flow	Category	Amount	Unit
F <sub>2</sub> Extraction of wheat starch, pro...	Agricultural/Feedstuff ...	1000.00000	kg	F <sub>2</sub> Wheat bran, from wheat starch extraction, at p...	Transform...	176.00000	kg
F <sub>2</sub> Soft wheat grain, conventional...	Transformation/Cereal ...	1000.00000	kg	F <sub>2</sub> Wheat gluten feed, from wheat starch extraction, ...	Transform...	220.00000	kg
F <sub>2</sub> Transport, freight, lorry, unspe...	Others/Ecoinvent cut-o...	50.00000	t*km	F <sub>2</sub> Wheat gluten meal, from wheat starch extraction,...	Transform...	93.00000	kg
				F <sub>2</sub> Wheat starch slurry, from wheat starch extraction,...	Transform...	419.00000	kg
				F <sub>2</sub> Wheat starch, from wheat starch extraction, at pla...	Transform...	540.00000	kg

Figure 14 Agrifootprint data modelling for multifunctional processes

For this case, the impact of the whole process can be easily derived by replacing the output flows referring to the physical flows by a virtual flow representing the sum of the output flows, the unit will be set to one ton, as a reference unit since the mass of the output vary between lca/Mfa models.

Output flow after changes



Flow	Category	Amount	Unit	Costs/Rev...
F <sub>2</sub> Process amidonnerie		1.00000	t	

It becomes unnecessarily complicated<sup>42</sup> when inventories are produced separately for each product and co-product of multifunctional processes, since the data do not refer to a multi-stream process, but to its partition on each output flow. This was the case for the ACYVIA data, moreover the values filled in for the inputs/outputs were based on formulas with parameters, that pre-included the allocation coefficient, as a result it bypassed the functionality of the lca software to give the user the freedom in choosing the allocation procedure.

F <sub>2</sub> Cheese production; from raw ...	Agricultural	0.00328822/(Qc*DMc /((Qp*DMp + Qw*DMw + Qc*DMc+ Qwc*DMwc+ Q...
F <sub>2</sub> Cheese production; from raw ...	Agricultural	0.556447298/(Qper*DMper /((Qp*DMp + Qw*DMw + Qc*DMc+ Qwc*DMw...
F <sub>2</sub> Cheese production; from raw...	Agricultural	1/(Qp*DMp /((Qp*DMp + Qw*DMw + Qc*DMc+ Qwc*DMwc+ Qper*D...

Figure 15 ACYVIA inventory modelling example

For this issue, the retrieval of un-allocated multifunctional datasets was proceeded as follow:

All the inputs and biosphere<sup>43</sup> emissions of the allocated data were duplicated in a new created dataset, the value amounts were related to a unit of outflow, a unit of outflow is equivalent to the sum of all output flows, the product flows (what satisfies the functional unit) were then replaced by a virtual flow with a value of 1. When the datasets were separated by product flow, the same method was used for global flows that are not specific to a sub-process (electricity, gas, water.), the values amount of the sub-processes were calculated with the following equation:  $V_{sp} = \sum V_a \cdot \frac{F_a}{F_t}$

V<sub>sp</sub> = Value of the unallocated sub-process; V<sub>a</sub> = allocated amount of the sub-process to the product a; F<sub>a</sub> = mass of the flow a; F<sub>t</sub> = mass of all the outflows.

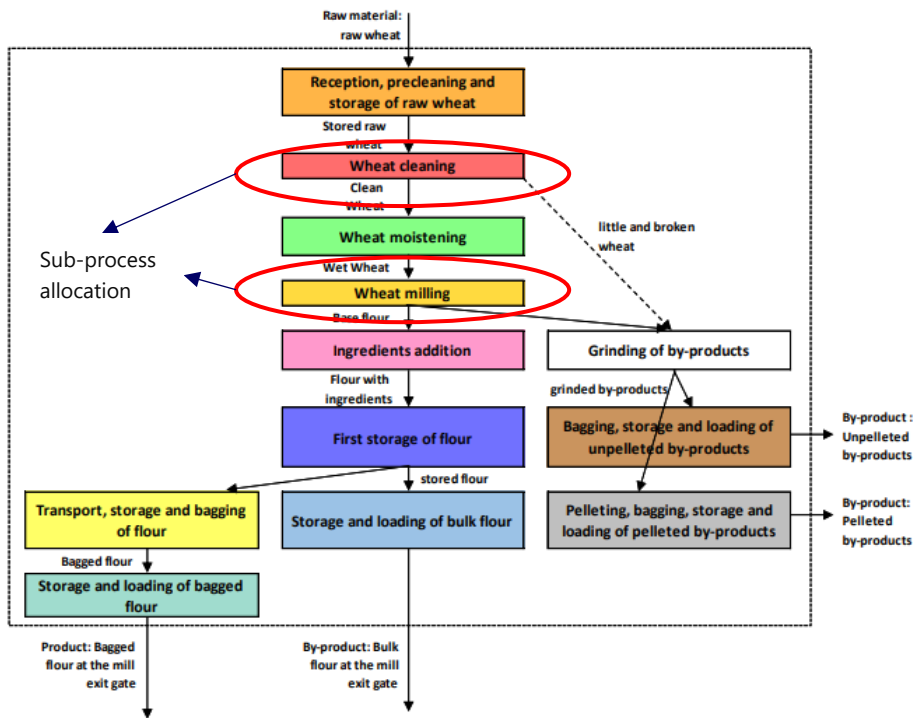
In the inputs all the sub-processes are considered, including the ones exclusive to a product or co-product, the idea is to normalise the impacts to an output unit, it is assumed, that the total mass output of an agrifood process is equivalent, between LCA/MFA models, motivating the normalisation on the output, another possible way would be to normalize on the raw food input. The multifunctionality solving phase will be made afterwards, the advantage of having unallocated datasets is to move the choice of the method for solving multifunctionality to the lca/mfa practionner after the harmonisation.

<sup>42</sup> This task could easily be avoided if unallocated datasets were initially included in the agribalyse database. A broader reflection on this can be found in the "limits and discussions" section.

<sup>43</sup> Exchange flows with Nature in the form of elementary flows.

## How to deal with multi-allocation processes?

In Acyvia database, we have encountered some multifunctional processes where the partitioning of impacts wasn't done at one shot in the macro level process, but through it's different multifunctional subprocesses, it was the case of the wheat milling process, moreover the allocation differentiated global flows from sub-processes. As shown in fig 18, two sub-processes were allocated based on economic values: the wheat cleaning (in red) producing clean wheat (an input for flour) and little and broken wheat (an input for by-products), the wheat milling, the main unit process, producing base flour and by-products.



**Figure 16** Milling process diagram in ACYVIA

The emerging question is then, **which allocation value to choose from for reversing the method to get the product impacts?**

When many allocation values exist in the same process, we suggest to calculate the average allocation value through the following equation:

$$\text{Economic allocation of product A} = \frac{\text{Original product A impacts}}{\text{Unallocated process impacts/Yield ratio}}$$

The conversion ratio of a product is the ratio of its mass value to the raw material input mass value e.g for one unit of wheat how much we get of flour. The average allocation value will allow to return to the exact impact results of an output product, due to the linear equation of allocation:

$$\text{Unitary Impacts of product A} = \text{process unitary}^{44} \text{ impacts} \times \text{economic allocation coefficient} \times \text{coefficient ratio inverse}^{45}$$

This is of course valid as long as the mass physical repartition between products/co-products is kept the same across models (MFA/LCA). When the physical repartition varies significantly, we recommend to proceed with dry mass values for allocation in the MFA model, since the difference is usually accounted for moisture level variation (the case of the starch sector). it is unusual for the multi-output physical breakdown to be exactly the same

<sup>44</sup> The reference unit can either be the sum of outflows or one unit input depending on the data

<sup>45</sup> To normalise the impacts to one unit mass equivalent to the input.

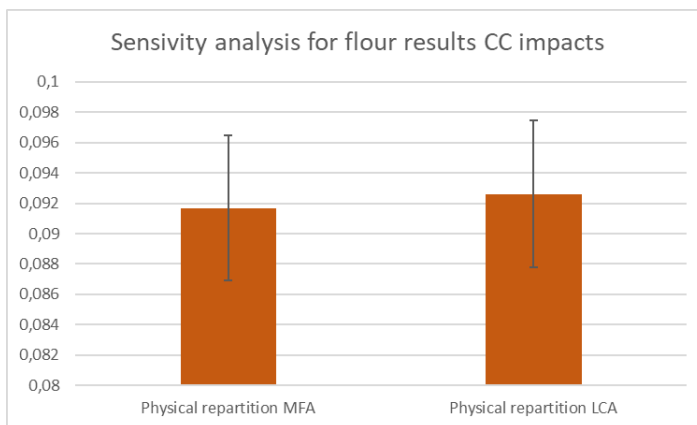
between MFA and LCA, for instance the milling process, which is a relatively simple and well-known industrial process is modelled with <10% differences in values across MFA/LCA. The significance of this variation on the results was assessed through a sensivity analysis, and analysed in regard to the base uncertainty.

The base uncertainty of each product was estimated as follow: For each flow product we have run 1000 iterations monte carlo simulations, then calculated the coefficient of variation (RSD) of the impacts of each flow product of the system (4), since the products we are investigating are at a larger aggregated level, we calculated the quadratic weighed average impacts of their disaggregated product types.

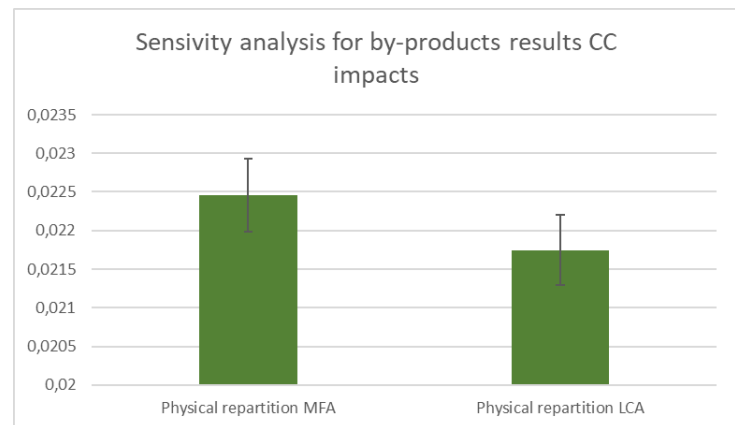
We selected two impact indicators: Climate change and acidification.

Model	Climate change GWP100 (T Co2 eq)	Acidification (Mol H+ eq)	Variability in %	Physical repartitions
<b>Wheat flour</b>				
MFA	0,09167358	0,727426517	<b>1,02%</b>	<b>0,784</b>
LCA	0,092618668	0,734925759		<b>0,776</b>
<b>Milling by-products</b>				
MFA	0,022955968	0,130848844	<b>3,24%</b>	<b>0,216</b>
LCA	0,021747759	0,123962063		<b>0,224</b>
<b>Base uncertainty</b>				
Wheat flour	5,209%	3,691%		
Milling by-products	2,107%	1,594%		

**Table 3** variability analysis of the impacts according to the multi-output physical distribution MFA/LCA



**Figure 18** Sensivity analysis flour wheat



**Figure 17** Sensivity analysis Milling by-products

The variability of the results regarding physical modelling is strongly linked to the relative difference in the physical repartition between models, as the wheat flour accounts for most of the milling production, the relative difference is low, so the variability of impacts. In contrast of the by-products where the relative difference is higher due to lower absolute share value. Compared with base uncertainties, the variability rate of wheat flour impacts due to physical modelling is within the margin of uncertainty for both climate change and Acidification impacts, thus it is not significant. While it is significant for By-products, we can conclude therefore, that this change in physical repartition may significantly affects the impacts results of product-coproducts with the lowest physical proportion.

## Impacts transfer of final consumption

As stated earlier, in Scalable a way to assess the environmental aspect of vulnerability induced by an activity (an agri-food sector) is to spatially distinguish between impacts occurring within and outside the territory under study. This can be done through Spatially differentiated LCA modelling ((Nitschelm et al., [2016](#)), the aim is to enhance the accuracy of the modelling by including spatial information through the different LCA stages, indeed the environmental impacts related to a flow emission, depend as much on the nature and quantity of the flow as on the receiving environment (this does not apply to the Climate change impact category, but remain true for other impacts categories). The inclusion of spatial information was mainly done for the LCI assessment phase, where spatially differentiated CFs were developed, through the Impact world+ method as an example (Bull et al. [2014](#)). Some studies added spatial information in the inventory phase (Dresen & Jandewerth, [2012](#)), by using spatially explicit databases with high spatial resolution data (country-wide) and Geographical information systems to trace emissions to their effective origins.

Due to the limited scope of the internship, the impacts results of the Fsc weren't spatialized, but even without proper spatialization of the impacts we can still separate the ones occurring in the territory and out of it by taking a consumption-based approach, that is, classifying the impacts based on the origin of the final products consumed by the population of a territory, for the sake of simplicity but also to reduce the uncertainties we will take two types of impacts : out of territory impacts embedded in the imported products and in-territory impacts embedded in the products locally consumed.

The impacts of the final consumption are calculated as follow = impacts of the production of the territorial FSC + (impacts of final imported products – impacts of final exported products). Based on the above we can derive a ratio that indicates at what extent the final consumption of a type of products induces a geographical transfer of environmental impacts.

**Intensity transfer ratio**=  $\frac{\text{Impacts of FC} - \text{impacts of Production}}{\text{impacts of FC}}$  if the ratio is positive, this can be interpreted as a transfer of impacts due to the final consumption of a group of products to out of the territory. Conversely if the ratio is negative, this means that the territory internalises a portion of the impacts related to the final consumption of other territories. There are many assumptions behind this indicator, first is the assumption that all or almost all impacts of local production are occurring locally, this may be true for countries with traditional low industrialised agriculture where feed input is bought locally<sup>46</sup> and few fertilisers are imported. However, in France the animal feed relies strongly on imported inputs mainly soybean meals from Brazil (Solagro, [2022](#)), thus the proposed indicator is blind on the impacts of the production of the inputs upstream. Provided that high spatial resolution<sup>47</sup> inventory data are available, it is possible to calculate the spatial impacts distribution of a production chain (from cradle) through processes location in mainstream Lca software. In this way the intensity transfer indicator can be adjusted as follows:

**Refined intensity transfer ratio**=  $\frac{\text{Impacts of FC} - (\text{impacts of Production} * \text{PT})}{\text{impacts of FC}}$  where PT is the part of the impacts of production occurring in the territory. In reality It is rare to have a precise spatial information on the location of processes in Lca, in ecoinvent database the data are spatially differentiated by regions RER (Europe), CH (Switzerland) and rest-of-the word. If the data is representative of the technological process but not geographically e.g a RER steel process representative enough of a Spanish steel plant, one can change the meta-data on location in the software to get a tweaked but perhaps better view on the geographical distribution of impacts. This is of course a workaround, country-specific inventories have to be created in the long-run, which is the expected output of the Ef project.

<sup>46</sup> By locally we mean in the country boundaries

<sup>47</sup> At least country-level resolution

## Results:

Although all impacts categories can be computed, we selected 5 indicators which covers two types of damages: Human health (toxicity cancer/non-cancer) and ecosystem health (Acidification and eutrophication), Climate change is linked to both damages. Due to time constraints, the resource depletion impacts weren't considered. For the sake of illustration and in regard to the current geopolitical setup<sup>48</sup>, an indicator of cumulative fossil energy use was computed for the oats supply chain.

Helper to interpret category indicators:

**Acidification:** Mmol H+ eq, is millions of mol H+ equivalent, unit of characterisation of acidification potential, it can be interpreted as the acidifying potential of 12 590 m3 of hydrochloric acid (37% concentration).

**Human toxicity:** CTUh (comparative toxic units human) is the unit of characterisation of human toxicity in usetox model, it refers to the estimated increase in morbidity (cancer or non-cancer) in the total human population, 179.6 CTUh means a potential increase of 179 cancer cases for the FSC of soft wheat.

## National scale food supply chains: the case of cereals

### Soft Wheat

The impact category	Production chain approach	Consumption based approach	ER production chain
Climate change	13,84 Mt Co2 eq	7,1 Mt Co2 eq	14.74 Mt CO2 eq
Soil and freshwater Acidification	262 Mmol H+ eq	152 Mmol H+ eq	314 Mmol H+ eq
Human toxicity Cancer	202 CTUh	92 CTUh	230 CTUh
Human toxicity non-Cancer	318 CTUh	251.3 CTUh	370 CTUh
Freshwater Eutrophication	4572.6 T P eq	2472.6T P eq	4603 T P eq

**Table 4** Soft wheat results, ER : extended responsibility

Overall, the consumption-based impacts of the soft wheat supply chain are lower than the production chain impacts (including exports), which is a normal pattern for net exporters agri-food chains, in other words in a vulnerability lens, France endures more environmental impacts that what is needed for its domestic consumption of soft wheat and derived products, incorporating the soft wheat consumption environmental footprint of other countries, mostly north Africa and China (Franceagrimer). This analysis is relevant for local/regional impacts like eutrophication and acidification, since these impacts are mostly occurring at the crop field level, by the excessive phosphorous emissions to soils from fertilisers application in the case of freshwater eutrophication and the ammonia emissions to air from Urea ammonium nitrate fertilisers in the case of acidification. The social acceptability of internalising external consumption environmental footprints is to be weighed against the economic gains of exports, ultimately the question is whether it is acceptable to put supplementary environmental pressure in a territory for non-alimentary purposes (economic revenues from exports), the compromise should be discussed against the territorial carrying capacity (at what extents the supplementary environmental pressure is threatening the regional environmental boundaries) , we will provide more details on the absolute environmental pressure of the soft wheat production in the "perspectives" section.

### Corn

<sup>48</sup> This document was produced after the invasion of Ukraine by Russia in 2022.

The impact category	Production chain approach	Consumption based approach	ER production chain
Climate change	5.11 Mt Co2 eq	1.56 Mt Co2 eq	5.96 Mt Co2 eq
Soil and freshwater Acidification	133 Mmol H+eq	110 Mmol H+ eq	140.9 Mmol H+ eq
Human toxicity Cancer	106 CTUh	13 CTUh	148 CTUh
Human toxicity non-Cancer	-214 CTUh	204 CTUh	-112 CTUh
Freshwater eutrophication	3102T P eq	995 T P eq	3220 T P eq

**Table 5** Corn results ER: extended responsibility

Surprisingly, for the corn food supply chain, the impacts on non-cancer human toxicity are negative, meaning the activity of the corn food system helps mitigate the toxicity effects of agriculture on humans, this can be counterintuitive if we take a perspective where anthropogenic activities lead systematically to environmental deterioration, but is explained by the negative zinc balance in the LCI of French average corn production, meaning a removal of zinc from soils, indeed corn is one of most responsive crops to zinc deficiency<sup>49</sup>needing high doses of zinc. Thus, the corn plant absorbs zinc in excess in agricultural soils and Zinc is considered a toxic substance. It is important to note that the reduction in non-cancer toxicity linked to zinc removal from corn plants counteract all the toxic non-cancer emissions impacts of the whole life cycle (including the production of fertilisers and agricultural machinery, emissions from diesel combustion etc.) of a corn crop production expressed in a year.

## Oats

The impact category	Production chain approach	Consumption based approach	ER production chain
Climate change	0,158 Mt Co2 eq	0.13 Mt Co2 eq	0.167 Mt Co2 eq
Soil and freshwater Acidification	3.9 Mmol h+ eq	3.2 Mmol h+ eq	
Human toxicity Cancer	2 CTUh	2 CTUh	
Human toxicity non-Cancer	28 CTUh	21 CTUh	
Freshwater eutrophication	79.6 T P eq	64.3 T P eq	
Cumulative fossil energy demand	836 TJ	/////	/////

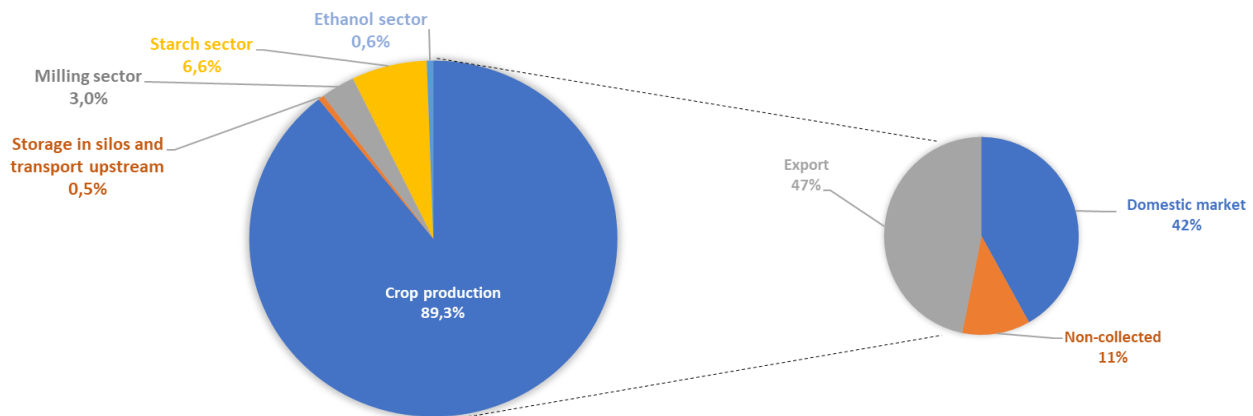
**Table 6** Oats Food supply chain impacts results ER: extended responsibility

The results for oats are consistent with the low volume of French oats production for 2015 revolving around less than half a million ton. As specified earlier, for illustrative purposes we also calculated the fossil energy demand for the oats production (including storage in bins), for the year 2015 the oats production including the inputs required 836 TJ of fossil energy, 53% in the mean of natural gas mainly for the production of Nitrogen fertilisers, oil comes close at 46% mainly fuelling agricultural vehicles and machines. This highlights the profound dependence of modern agriculture to fossil fuels. Assuming the LCA data are reliable, the cumulative energy requirement is equivalent to 11.4 million m<sup>3</sup> of natural gas and 8000 tons of crude oil.

<sup>49</sup> University of minnesota [link](#).

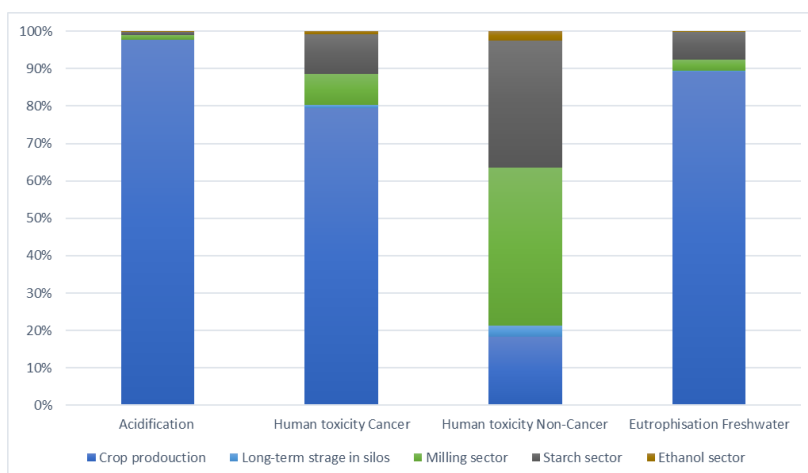
## Contribution analysis

### Soft wheat



**Figure 19** Contribution analysis of the soft wheat FSC By sectors and production destination for climate change

As shown in Fig 12, the first contributor to the climate change impacts of the soft wheat FSC is the agriculture stage with 89% of the total impacts, this is on par with the existing literature in terms of order of magnitude (Poore & Nemecek, 2018). We decomposed these impacts by crop destination, thus 47% can be attributed to exports, 42% for domestic market, and finally 11% for the non-collected wheat grains, that is the amount of soft wheat consumed or stored on farm and not added to the market. Since we assume a linear relation between mass flows and unitary impacts<sup>50</sup>, it is very consistent with the structure of crop mass flows; France is one of the largest exporters of soft wheat in the world. *What's is perhaps interesting is the distribution of the impact between the processing sectors*, The starch sector comes first with 6.6% of the FSC GHG impacts but 61.7% of the impacts attributed to the processing stage, while it delivers less than 30% of the processed products, this is due to the high carbon intensity of the starch industrial process requiring a great amount of heat for the drying step, mostly provided by fossil sources (natural gas). The distribution of impacts in the production chain is similar for the other impacts categories calculated, except for toxicity indicators, due to the production process of packaging (cardboard boxes) for starch and milling industry (Fig15).



**Figure 20** Contribution analysis of the soft wheat FSC on non-climate change impacts

<sup>50</sup> We insist on this aspect, because consequential modelling in LCA can lead to non-linearities, which we believe is more realist and representative of the real world, for example beyond a certain level of production, the type of land use change can vary (from pasture to culture, to forests to culture) strongly increasing the GHG emissions per unit of crops.

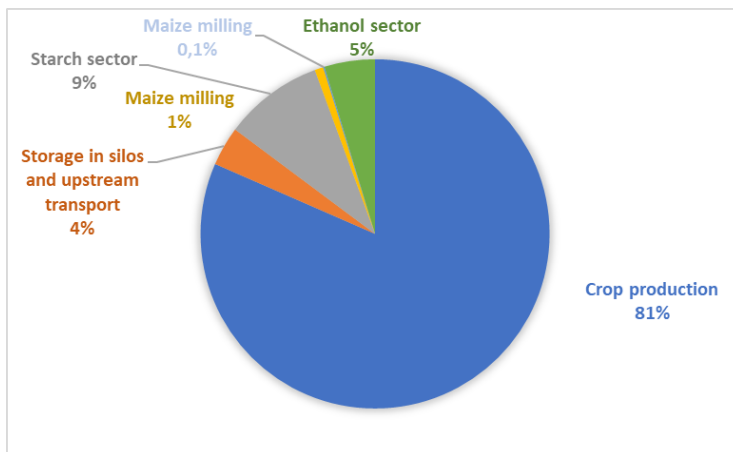
Regarding the imports of final products, we investigated the part of international transports in the impacts, below is the results for the imports of wheat grain, the biggest imported flow.

Impact indicators	Transport contribution	Production contribution
Climate change	12,42%	87,58%
Soil and freshwater acidification	6,025312%	93,974688%
Human toxicity cancer	99,99371%	0,0063%
Freshwater eutrophication	3,84%	96,16%

**Table 7** the embedded impacts of transports in imported wheat grains

We can notice the very high contribution of the transport to the human toxicity impacts, this can be explained by the inclusion of infrastructure (road building, ports...) in transport LCA data, in crop production the data as well considered the infrastructure (agricultural machinery and farm buildings), however the transports are much infrastructure intensive than agriculture e.g for the transoceanic sea transport in addition to the building of the ship, a seaport is required for the service of sea transport.

### Corn



The Corn FSC shares the same industrial processes with wheat; thus, the structure of the impacts is very similar, with the production phase being the prominent (81%), followed by the starch industry (9%).

**Figure 21** Contribution analysis of the national corn Production chain for Climate change

## Multi-scale assessment: the case of the dairy industry national and regional impacts

### National dairy

The impact category	Production chain approach
Climate change	35.05 Mt Co2 eq
Soil and freshwater Acidification	353 Mmol h+ eq
Human toxicity Cancer	14CTUh
Human toxicity non-Cancer	679 CTUh
Freshwater eutrophication	4488 T P eq

**Table 8** National dairy Impacts

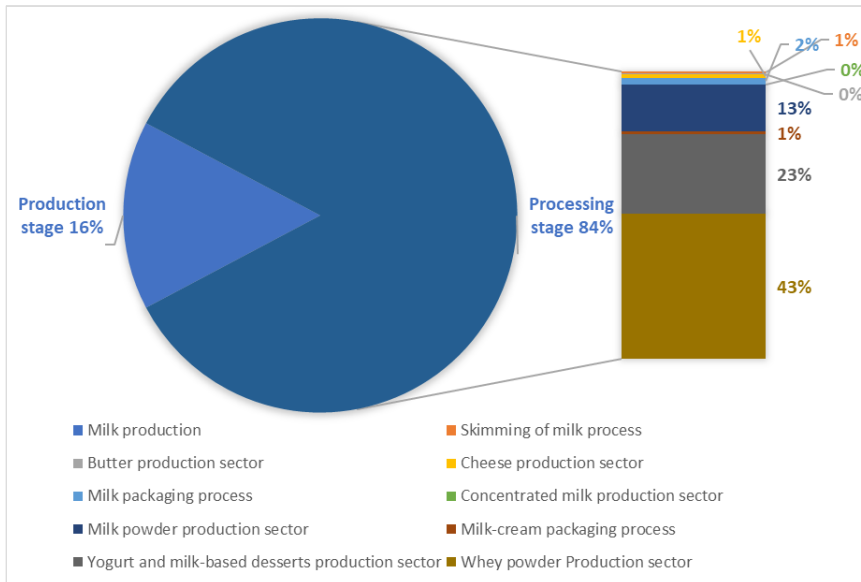
The dairy food supply chain is characterized by high climate change impacts, due to methane emissions from cattle. The distribution between the production and processing stage is similar with the cereal food systems.



## Regional

To illustrate the regional variation in the structure of dairy production, we selected two regions that are either net exporter (Bretagne) or net importer (Ile de France) of dairy products. The objective is to highlight the impacts of regional specialisation in terms of production/processing on the environmental impacts structure, and to further link it to vulnerabilities concerns.

### Ile de France



**Figure 22** Contribution analysis of the IDF dairy FSC

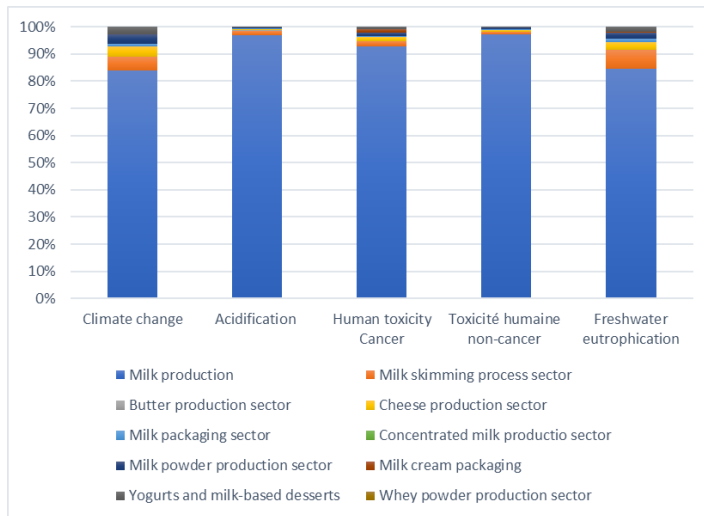
Taking a territorial production perspective, in Ile de France, for the dairy production chain, in contrast to the contribution patterns presented earlier, it is the processing phase the prominent contributor to climate change, this is linked to its material flow's structure, importing most of its raw materials that are processed further in the value chain (milk, whey etc.). That means that the dairy food system of the region is specialised in processing. In terms of the distribution of GHG emissions between the processing sectors, the whey production sector comes first with 43% of the total, mainly due to the relative high mass production of whey powder (38% of the processed dairy products).

Moving to a consumption approach, the consumption of the dairy products in Ile de France Induce a very high transfer of impacts, 87% to be precise, due to the considerable share of imports in final consumption, namely 82% of the final consumption of packaged milk is imported. In an increasingly unstable world, having this low self-sufficiency rate is problematic, even though this type products are far from being essential to the regional food security, it highlight the weakness of their supply. However, the possibility of food self-sufficiency in such a region is disputable and far from being obvious<sup>51</sup>.

<sup>51</sup><https://www.institutmomentum.org/vers-lautonomie-alimentaire-de-lile-de-france-le-scenario-afterres-francilien-par-christian-couturier/>

## Bretagne

As presented below in fig. 23, the Bretagne Dairy food production chain, share a similar contribution structure with the other food systems studied.



**Figure 23** Contribution analysis Bretagne Dairy FSC

Based on the fact that it is a net exporter territory in terms of dairy products with self-sufficiency, we would expect an internalisation of impacts, however since the dairy production relies at a high rate on imports, through cattle feed, we calculated the refined impacts transfer rate that includes upstream impacts. Thus *at least 27%* of the impacts related to the consumption of dairy products in Bretagne are out of the territory.

## Sensitivity analysis

### Regarding LCIA methods

We assessed the sensitivity of the results to the impact assessment method by comparing the method used (EF2.0) to the latest IPCC report (AR6) GWP values (IPCC, Foster et al. [2021](#)). We restricted the analysis to the production chain impacts.

Food production chain	GWP 100 impacts EF 2.0	GWP 100 impacts IPCC 2021 AR6	Change in %
Soft wheat	14.1 Mt co2 eq	13.1 Mt Co2 eq	<b>-7.09%</b>
Corn	5.11 Mt Co2 eq	4.70 Mt Co2 eq	<b>-8.02%</b>
Dairy	35.05 Mt co2 eq	30.58 Mt co2 eq	<b>-12.75%</b>

**Table 9** Sensitivity analysis regarding LCIA methods

Overall, updating CFs for climate change lowered the impacts, this is caused by lower global warming potentials values for methane and nitrous oxide in the last IPCC report, due to an improved modelling of their lifespan in atmosphere by the scientific community. Knowing that most climate change impacts in livestock are due to CH<sub>4</sub> and NO<sub>2</sub> gases, this variability is very significant for the dairy food production chain.

## Limits and discussions:

### ***A need for Consequential approach:***

The main difference between the attributional and consequential approaches is the aim (descriptive vs decision support), in fact both approaches lead to a decision of technological choices or the substitution of products/systems. (Consequential-LCA.2021).

To help identify the appropriate approach, the ILCD handbook proposes three types of decision-making contexts in LCA (European commission, 2010): the Type A context for micro-level decision-support (eco-design, of a product or service etc.) the type B context for meso-macro scale decision-support (change in the foreground system having large scale consequences) and the Type C devoted to an "accounting" objective, this last type is further classified in two categories, based on whether the interactions with other systems are considered (C1) or not (C2).

Decision-context	Type A	Type B	Type C1	Type C2
Modelling approach	Attributional Lci modelling	Consequential LCI modelling	Consequential	Attributional

The ultimate objective of our study on French food supply chains is clearly policy-oriented decision support, which is closest to the type B decision-context, thus a consequential modelling is necessary to include background changes. Marginal production data and system expansion (to deal with multifunctional processes) could be integrated in the background modelling of Agribalyse. This can potentially lead to significant change in results (Thomassen et al., 2008).

### ***A strong dependency on LCA data quality and database construction:***

In the coupling of MFA and LCA, a great amount of work was caused by the LCI data construction in the ACYVIA Life cycle inventory project, although it greatly followed the ISO hierarchy for multi-functionality solving strategies, it made the LCA data more difficult to couple with other data (MFA data in particular). As a consequence, the method we followed is binded to the ACYVIA inventory modelling case. Furthermore, the reliability and scope of LCA data in Agribalyse are strongly dependent on the initial data provider, creating inconsistencies when using data from different data providers, as an example all the data produced through the ACYVIA project included the infrastructure (buildings etc.), which were excluded both in the data produced by Agrifootprint and Koch consulting (for packaged products). We had to manually harmonise the inventory scope (infrastructure) between sectors. This harmonisation work would not be necessary if the Agribalyse database imposed initially a common cut off rule on all its datasets. Even more important, some data were based on proxies (Yogurts based on a Canadian inventory data) that were poorly representative of the French context. We had to check the representativeness of each dataset. Thus, the results in term of absolute impacts are very linked to the lca data quality. Which is beyond the perimeter of our work.

### ***The need for multi-sector reconciliation (Corn/wheat):***

The starch industry relies on a cross-sector process, using a variety of raw materials (Corn, wheat, potato.) as inputs for the production of starch and by-products, in the MFA model the gluten and starch outputs are assumed to be from mixed origins (Corn and wheat essentially). Therefore, a multi-sector data reconciliation is needed to differentiate these types of flows. Moreover, we don't know the type of starch imported in each system, adding uncertainties to the results.

### ***Uncertainties for transport mode and distances:***

There is a high level of uncertainty about the modes of transport used for each flow of imported products. Due to an insufficient level of disaggregation in the Sitram database to link it to the MFA product flows, the categories in the Sitram database are sometimes grouped together. A very high number of products, such as starch, which was grouped together with gluten, given that there are five types of starch and two types of gluten, in addition to gluten feeds for animal feed. As regards transport distances, the CERDI database provides reliable data on maritime transport distances, but for the other modes of transport (road, rail, river), we used the less accurate Searates database and due to a lack of data on river and rail distances, road distances were used instead. Therefore, there are uncertainties about the impact of transport on import flows. Nevertheless, the contribution of transport to the impacts of import flows was consistently very low except for human toxicity, hence the low significance of these uncertainties on imported flows and further consumption-based impacts.

### ***Uncertainties in the background MFA models:***

Beyond LCA related uncertainties, the MFA model, has also a great deal of uncertainties, the data reconciliation procedure proposed by Courtonne, Alapetite and colleagues (2015) to estimate supply chain flow values when data is lacking, is based on the data classification of Brunner and Reichberg (2017), data are classified as measured and unmeasured, the first class is solved through least square optimization with constraints about the physical properties of the processes (conversion rates, moisture rates..), the latter is solved in the same way if the data are determinable (observable), however when data are undeterminable, the optimization program is set free to compute data and produce flow values within a defined interval. As a consequence, there may be considerable uncertainties in this type of data.

### ***Lack of spatial resolution for regional impacts transfer:***

The impact transfer ratios proposed are not suitable to properly trace inter-regional impacts transfer, due to the low spatialisation of LCA inventories, moreover it would be challenging to trace the geographical origins of all the flows in the inventories, it will require a massive information system and extensive bottom-up data collection. For these reasons the ratios should only be used for illustrative purposes of the environmental side of low territorial self-sufficiency. It is not reliable for decision support. EE-MRIO approaches are more suitable to trace trade related impacts transfer at the country-level (Wood et al. 2015)

### ***The representativeness in agricultural Lca's :***

One of the most prominent issues in agriculture LCA is the inclusion of farm production systems diversity (Dijkman et al. 2018), Most LCA studies are at the farm level, with specific samples that do not fully integrate the regional and intra-regional diversity of cultivation practices. For example, for the production of conventional soft wheat in Agribalyse, the national average data was calculated from 11 case study farms that were considered representative of the national average, none of the farms was located in the north region, one of the most important regions in terms of soft wheat production. It is therefore not possible to extrapolate the national data downwards, given the differences in practices between regions and even between sub-regions. A way to better consider regional farming activities is to build on farming typologies based on Agrarian systems diagnosis (Pradeleix et al. 2021).

## Perspectives:

### **Software integration**

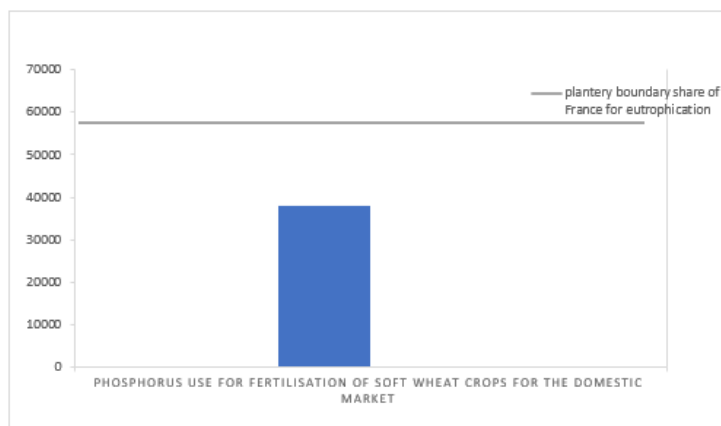
The lack of software integration has severely limited the possibilities of coupling MFA/LCA, in the future a common software interface would enable faster coupling and calculations, this could be implemented through the Brightway software (Mutel, [2017](#)) or the python Openlca interface. Furthermore, this would allow to automate the improvement of MFA models with LCA data, when the latter is more precise.

### **Extending the coupling to other agricultural sectors:**

The next step would be to continue the coupling with other food supply chains, the Sugar beet Sector is a very good example with multiple multi-output processes.

### **Moving to an absolute paradigm of sustainability**

Absolute sustainability is an increasingly studied new paradigm in sustainability assessment (Bjørn et al., [2020](#)). The core idea is to switch from a relative/comparative sustainability assessment (which system is better) to an absolute assessment regarding absolute environmental thresholds (is it good enough?) portrayed by the planetary boundaries framework. A part of the sustainable share is allocated to the system under study, based on various sharing principles. Below is an attempt to integrate the absolute sustainability paradigm for the soft wheat production, we used the eutrophication planetary boundary, downsized to France following the epc principle (equal per capita), this principle was selected for its simplicity although other sharing principles are possible (See Bjørn et al., [2020](#)). The eutrophication potential of the soft wheat production was assessed by average phosphorus fertilisers use (Agreste<sup>52</sup> 2017).



Based on the absolute sustainability paradigm the soft wheat French production uses around 74% of the eutrophication "budget" of France<sup>53</sup>.

### **Integration of air transportation impacts in imported flows**

Air transportation is uncommon in the FSC's studied, but was encountered for starch/gluten incoming flows at 0.2% of the transported volumes, despite this very low value, it would be interesting to include its impacts, knowing that one t.km of air freight transport is accountable for about 100 times more GHG emissions than sea transport (based on ecoinvent 3.4 data).

<sup>52</sup> [Chiffres et données : Octobre 2020 Numéro 9 - Agreste \(agriculture.gouv.fr\)](#)

<sup>53</sup> This of course remains an illustrative example of an absolute assessment of sustainability for an agricultural sector, as the carrying capacity does not take into account regional and inter-country variability, the share of the carrying capacity is assumed equal.

## Conclusion

The work carried out during this internship highlighted the inconsistencies between the MFA and LCA models and proposed an attempt to resolve them. The data scope change can be easily automated where the reconstitution of unallocated datasets is perhaps more difficult to automate, and will still require human verification, which is also applicable to data harmonisation tasks in general. Nevertheless, improved LCA database development rules for data interoperability, would significantly reduce these inconsistencies from the source and avoid the bulk of the work presented earlier. Ecoinvent already provides Unallocated datasets, still, the complexity of the data from the ACYVIA project is due in particular to a more rigorous compliance with the methodological recommendations regarding allocation rules by the ISO standard, therefore the hierarchy of allocation rules as defined in ISO 14040 ([2006a](#)) reduces the interoperability of the data with other methods and complicates the coupling process. I admit that the impacts results presented do not add original information to the scientific literature, in general it is already known that the production stage is the most important in the environmental impacts of an agricultural product, at the level of the transfer of impacts, a more in-depth study has already been published by Courtonne ([2016](#)). Despite this, I believe that this work will at least shed some light on the limits to coupling between LCA and MFA models. beyond that, the question to ask is whether it is desirable to increase the complexity and sophistication of environmental modelling for decision support? Privlashivsky and searcy ([2021](#)) have recently highlighted this divergence of approaches in LCA community between the academic world and the decision makers (industrials), the first are more interested in improving the reliability and accuracy of LCA, where the latter are more concerned by simplifying ICA. I believe that in order to address the climate emergency, it is more useful to study why behaviours do not change at the individual level and decisions are not taken at the political level, because despite the robust knowledge we have about the facts and causes of climate change, as a society we still struggle to change at a sufficient pace for a sustainable future. We already know enough.

## Bibliography

- ADEME. (n.d.). Référentiel méthodologique permettant la production de données d'ICV pour la transformation agro-alimentaire. La librairie ADEME. Retrieved 3 July 2022, from <https://librairie.ademe.fr/consommer-autrement/2029-referentiel-methodologique-permettant-la-production-de-donnees-d-icv-pour-la-transformation-agro-alimentaire.html>
- AF filières. (2017). <https://www.flux-biomasse.fr/>
- Asselin-Balençon A., Broekema R., Teulon H., Gastaldi G., Houssier J., Moutia A., Rousseau, V., Wermeille A., Colomb V. 2020. AGRIBALYSE v3.0: la base de données française d'ICV sur l'Agriculture et l'Alimentation. Methodology for the food products. Ed. ADEME 2020.
- Baccini, P., & Brunner, P. H. (2012). *Metabolism of the Anthroposphere: Analysis, Evaluation, Design* (2nd ed.). MIT Press.
- Belyanovskaya, A. I., Laratte, B., Rajput, V. D., Perry, N., & Baranovskaya, N. V. (2020). The Innovation of the characterisation factor estimation for LCA in the USETOX model. *Journal of Cleaner Production*, 270, 122432. <https://doi.org/10.1016/j.jclepro.2020.122432>
- Bertoli, S., Goujon, M., & Santoni, O. (2016). The CERDI-seadistance database. <https://halshs.archives-ouvertes.fr/halshs-01288748>
- Birat, J.-P. (2021). MFA vs. LCA, particularly as environment management methods in industry: An opinion. *Matériaux & Techniques*, 108(5-6), 503.
- Bjørn, A., Moltesen, A., Laurent, A., Owsianiak, M., Corona, A., Birkved, M., & Hauschild, M. Z. (2017). Life Cycle Inventory Analysis. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 117–165). Springer International Publishing. [https://doi.org/10.1007/978-3-319-56475-3\\_9](https://doi.org/10.1007/978-3-319-56475-3_9)
- Bjørn, A., Owsianiak, M., Molin, C., & Hauschild, M. Z. (2018). LCA History. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Éds.), *Life Cycle Assessment: Theory and Practice* (p. 17-30). Springer International Publishing.
- Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., Hauschild, M. Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters, G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., & Ryberg, M. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environmental Research Letters*, 15(8), 083001. <https://doi.org/10.1088/1748-9326/ab89d7>
- Brunner, & Rechberger. (2016). *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*, Second Edition. CRC Press. <https://doi.org/10.1201/9781315313450> (P.124-126)
- Consequential-LCA (2021). Why and when? Last updated: 2021-08-20. [www.consequential-lca.org](http://www.consequential-lca.org).
- C. Bulle, M. Margni, O. Jolliet, R. Rosenbaum, S. Humbert, IMPACT World+ (2014) <http://www.impactworldplus.org/en/>
- Courtonne, J. (2016). Environmental assessment of territories through supply chain analysis: Biophysical accounting for deliberative decision-aiding [Phdthesis, Université Grenoble Alpes]. <https://tel.archives-ouvertes.fr/tel-01421664>
- Dorca-Preda, T., Fantke, P., Mogensen, L., & Knudsen, M. T. (2022). Towards a more comprehensive life cycle assessment framework for assessing toxicity-related impacts for livestock products: The case of Danish pork. *Science of The Total Environment*, 815, 152811. <https://doi.org/10.1016/j.scitotenv.2021.152811>
- Dijkman, T. J., Basset-Mens, C., Antón, A., & Núñez, M. (2018). LCA of Food and Agriculture. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 723–754). Springer International Publishing. [https://doi.org/10.1007/978-3-319-56475-3\\_29](https://doi.org/10.1007/978-3-319-56475-3_29)
- Djekic, I., Miocinovic, J., Tomasevic, I., Smigic, N., & Tomic, N. (2014). Environmental life-cycle assessment of various dairy products. *Journal of Cleaner Production*, 68, 64–72. <https://doi.org/10.1016/j.jclepro.2013.12.054>

- Dresen, B., & Jandewerth, M. (2012). Integration of spatial analyses into LCA—calculating GHG emissions with geoinformation systems. *The International Journal of Life Cycle Assessment*, 17(9), 1094–1103. <https://doi.org/10.1007/s11367-011-0378-3>
- European commission. (n.d.). The Combined Nomenclature. Retrieved 2 July 2022, from [https://ec.europa.eu/taxation\\_customs/business/calculation-customs-duties/customs-tariff/combined-nomenclature\\_en](https://ec.europa.eu/taxation_customs/business/calculation-customs-duties/customs-tariff/combined-nomenclature_en)
- European commission. (n.d.). Environmental Footprint. Retrieved 25 June 2022, from <https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html>
- European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010
- FAO. 2021. The State of Food and Agriculture 2021. Making agrifood systems more resilient to shocks and stresses. Rome, FAO. <https://doi.org/10.4060/cb4476en>
- Forster, P., T. Storelmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, <https://doi.org/10.1017/9781009157896.009>.
- Füssel, H.-M. (2007). Vulnerability: A generally applicable conceptual framework for climate change research. *Global Environmental Change*, 17(2), 155-167.
- Geels, F. W. (2005). The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technology Analysis & Strategic Management*, 17(4), 445–476. <https://doi.org/10.1080/09537320500357319>
- González-García, S., & Dias, A. C. (2019). Integrating lifecycle assessment and urban metabolism at city level: Comparison between Spanish cities. *Journal of Industrial Ecology*, 23(5), 1062–1076. <https://doi.org/10.1111/jiec.12844>
- Güereca, L. P., Padilla-Rivera, A., & Aguilar-Rivera, N. (2022). Life cycle assessment of nine representative agroindustrial systems of sugar production in Mexico. *Food and Bioproducts Processing*, 131, 164-175.
- Harchaoui, S. (2019). Modélisation des transitions en agriculture : Énergie, azote, et capacité nourricière de la France dans la longue durée (1882-2016) et prémices pour une généralisation à l'échelle mondiale [These de doctorat, Université de Paris (2019-...)]. <https://www.theses.fr/2019UNIP7003>
- IDELE, Gisements et valorisations des coproduits des industries agroalimentaires, 2017, p.38 [https://idele.fr/fileadmin/medias/Documents/Reseda\\_rapport\\_complet\\_gisements\\_coproduits.pdf](https://idele.fr/fileadmin/medias/Documents/Reseda_rapport_complet_gisements_coproduits.pdf)
- ISO. (n.d.). ISO 14040:2006a. ISO. Retrieved 23 May 2022, from <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html>
- ISO. (n.d.). ISO 14044:2006b. ISO. Retrieved 25 June 2022, from <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/84/38498.html>
- Jeswani, H. K., Azapagic, A., Schepelmann, P., & Ritthoff, M. (2010). Options for broadening and deepening the LCA approaches. *Journal of Cleaner Production*, 18(2), 120–127. <https://doi.org/10.1016/j.jclepro.2009.09.023>
- Jungbluth, N., Tietje, O., & Scholz, R. (2000). Food purchases: Impacts from the consumers' point of view investigated with a modular LCA. *The International Journal of Life Cycle Assessment*, 5, 134–142. <https://doi.org/10.1007/BF02978609>
- Lavers Westin, A., Kalmykova, Y., Rosado, L., Oliveira, F., Laurenti, R., & Rydberg, T. (2019). Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption. *Journal of Cleaner Production*, 226, 526–539. <https://doi.org/10.1016/j.jclepro.2019.04.036>



- Laurent, F. (2015). Évaluation des performances environnementales de l'insertion d'une filière de méthanisation centralisée au sein d'un territoire [These de doctorat, Rennes 1]. <https://www.theses.fr/2015REN1S022>
- Le Gallou, F., & Bouchon-Meunier, B. (Eds.). (1992). *Systémique: Théorie et applications* (Vol. 1–1, Issue 1). Lavoisier-Tec & Doc.
- Loiseau, E., Aissani, L., Le Féon, S., Laurent, F., Cerceau, J., Sala, S., & Roux, P. (2018). Territorial Life Cycle Assessment (LCA): What exactly is it about? A proposal towards using a common terminology and a research agenda. *Journal of Cleaner Production*, 176, 474–485. <https://doi.org/10.1016/j.jclepro.2017.12.169>
- Ludwig Won Bertalanffy, (1969) *General systems theory Foundations, Development, Applications*. (55-56p)
- Mackenzie, S. G., Leinonen, I., & Kyriazakis, I. (2017). The need for co-product allocation in the life cycle assessment of agricultural systems—Is “biophysical” allocation progress? *The International Journal of Life Cycle Assessment*, 22(2), 128–137. <https://doi.org/10.1007/s11367-016-1161-2>
- Meadows, D. H., Randers, J., & Meadows, D. L. (2013). *The Limits to Growth* (1972). In *The Limits to Growth* (1972) (pp. 101–116). Yale University Press. <https://doi.org/10.12987/9780300188479-012>
- Ministère de la transition écologique. (n.d.). Le parc de poids lourds en circulation est stable au 1er janvier 2020. Données et études statistiques pour le changement climatique, l'énergie, l'environnement, le logement, et les transports. Retrieved 3 July 2022, from <https://www.statistiques.developpement-durable.gouv.fr/le-parc-de-poids-lourds-en-circulation-est-stable-au-1er-janvier-2020>
- Molina, M. G. de, & Toledo, V. M. (2014). *The Social Metabolism: A Socio-Ecological Theory of Historical Change*. Springer.
- Moscovici, S., & Vignaux, G. (1994). Le concept de Thémata. In C. Guimelli (Ed.), *Structures et transformations des représentations sociales* (pp. 25-72). Neuchâtel: Delachaux et Niestlé.
- Muller, S., Boitier, B., Lai, F., & Villeneuve, J. (2019, November 6). Quel est le potentiel des bases de données EE-MRIO pour le suivi et l'analyse des impacts de la consommation française? avniR Conférence. <https://hal-brgm.archives-ouvertes.fr/hal-02296709>
- Mutel, C. (2017). Brightway: An open source framework for Life Cycle Assessment. *Journal of Open Source Software*, 2(12), 236. <https://doi.org/10.21105/joss.00236>
- Pryshlakivsky, J., & Searcy, C. (2021). Life Cycle Assessment as a decision-making tool: Practitioner and managerial considerations. *Journal of Cleaner Production*, 309, 127344. <https://doi.org/10.1016/j.jclepro.2021.127344>
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), 987–992. <https://doi.org/10.1126/science.aag0216>
- Nitschelm, L., Aubin, J., Corson, M. S., Viaud, V., & Walter, C. (2016). Spatial differentiation in Life Cycle Assessment LCA applied to an agricultural territory: Current practices and method development. *Journal of Cleaner Production*, 112, 2472–2484. <https://doi.org/10.1016/j.jclepro.2015.09.138>
- Nygren, J., & Antikainen. (2010). *Use of life cycle assessment (LCA) in global companies*. Finnish environment institute.
- Projet Scalable. (n.d.). Retrieved 24 June 2022, from <https://www.projet-scalable.fr/le-projet/>
- SeaRates. (n.d.). Online Freight Shipping & Transit Time Calculator at Searates.com. SeaRates. Retrieved 2 July 2022, from <https://www.searates.com/services/distances-time/>
- Simon, J. L. (1981). *The ultimate resource*. Princeton, N.J.: Princeton University Press. Chapter 3"Can the Supply of Natural Resources Really be Infinite? Yes!"
- Shahbudin, N. R., & Kamal, N. A. (2021). Establishment of material flow analysis (MFA) for heavy metals in a wastewater system. *Ain Shams Engineering Journal*, 12(2), 1407–1418. <https://doi.org/10.1016/j.asej.2020.10.009>

- Solagro. (2022). La face cachée de nos consommations Quelles surfaces agricoles et forestières importées? [https://solagro.org/images/imagesCK/files/publications/f117\\_brochure-importations-solagro-web.pdf](https://solagro.org/images/imagesCK/files/publications/f117_brochure-importations-solagro-web.pdf)
- Steubing, B., Mutel, C., Suter, F., & Hellweg, S. (2016). Streamlining scenario analysis and optimization of key choices in value chains using a modular LCA approach. *The International Journal of Life Cycle Assessment*, 21(4), 510–522.
- Rochat, D., Binder, C. R., Diaz, J., & Jolliet, O. (2013). Combining Material Flow Analysis, Life Cycle Assessment, and Multiattribute Utility Theory. *Journal of Industrial Ecology*, 17(5), 642–655. <https://doi.org/10.1111/jiec.12025>
- Rockström, J. and al. (2009). A safe operating space for humanity. *Nature*, 461(7263), 472–475. Ht
- Raupova, O., Kamahara, H., & Goto, N. (2014). Assessment of physical economy through economy-wide material flow analysis in developing Uzbekistan. *Resources, Conservation and Recycling*, 89, 76–85. <https://doi.org/10.1016/j.resconrec.2014.05.004>
- Thomassen, M. A., Dalgaard, R., Heijungs, R., & de Boer, I. (2008). Attributional and consequential LCA of milk production. *The International Journal of Life Cycle Assessment*, 13(4), 339–349. <https://doi.org/10.1007/s11367-008-0007-y>
- University of minnesota. (n.d.). Zinc for crop production. Retrieved 3 July 2022, from <https://extension.umn.edu/micro-and-secondary-macronutrients/zinc-crop-production>
- Weidema Bo, Market Information in Life Cycle Assessment, Danish Environmental Protection Agency, Copenhagen (2003) (Environmental Project no. 863) <http://lca-net.com/p/1078> (P14-15)
- Weidema, B. P., Pizzol, M., Schmidt, J., & Thoma, G. (2018). Attributional or consequential Life Cycle Assessment: A matter of social responsibility. *Journal of Cleaner Production*, 174, 305–314. <https://doi.org/10.1016/j.jclepro.2017.10.340>
- Wilfart, A., Gac, A., Salaün, Y., Aubin, J., & Espagnol, S. (2021). Allocation in the LCA of meat products: Is agreement possible? *Cleaner Environmental Systems*, 2, 100028. <https://doi.org/10.1016/j.cesys.2021.100028>
- Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., De Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J. H., Merciai, S., & Tukker, A. (2015). Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. *Sustainability*, 7(1), 138–163. <https://doi.org/10.3390/su7010138>



## Appendix 2: Supplementary information's for the soft wheat FSC

### Datasets used:

FSC sectors	Agribalyse Datasets
Crop production	Soft wheat grain, average from 11 optimized case study, basis scenario, at farm g
Milling sector	Global milling process; soft wheat, steel-roller-milled, industrial production; French production mix, at plant...
Starch sector	Wheat gluten feed, gluten meal, bran, starch and starch slurry - FR
Ethanol sector	Flegmasses, Ethanol and DDGS, from wheat distillation, at plant
Long-term storage	Customized data based on "Soft wheat grain stored and transported" dataset. Soft wheat was excluded from inventory.
Imported products	Environmental footprint datasets
Soft Wheat grains	Wheat grain; , at farm, technology mix, production mix, Location : GLO and EU28+ the impacts have been weighted based on origins of imports. (87% EU, 14% Non EU)
Flour	Wheat flour; , at plant, from dry milling, Location : BE, DE, ES, GB, IT, UE28+ the impacts have been weighted based on origins of imports.
Starch	Weighted average of : Potato starch dried; , at plant, from wet milling, production mix,EU+28 Maize starch, dried; , at plant, from wet milling, production mix,GLO Wheat starch; , at plant, from wet milling, production mix,GLO
Gluten	Wheat gluten meal; , at plant, from wet milling, production mix,UE28+
Wheat gluten feed	Wheat gluten feed; , at plant, from wet milling, production mix,EU+28
Wheat bran	Wheat bran; , at plant, from wet milling, EU+28
Wheat middlings	Wheat middlings & feed; , at plant, from dry milling, production mix,EU+28

**Cut of rules:** infrastructure is excluded to harmonise the different sectors. The malting sector was excluded due to a lack of lca data, the amounts of food processed is very marginal in this sector, thus having nearly no effects on the global environmental impacts of the food supply chain.

### Imported Starch

Since the data on the type of imported Starch was not available, we calculated the unit impacts of imported starch in the soft wheat FSC, by weighing the impacts in regard of the distribution between the different types (Wheat, corn, potato), the data on type distribution was derived from customs. Therefore, we assumed the type of starch imported was equivalent to the average mix in in the same year.

### Perimeter harmonisation:

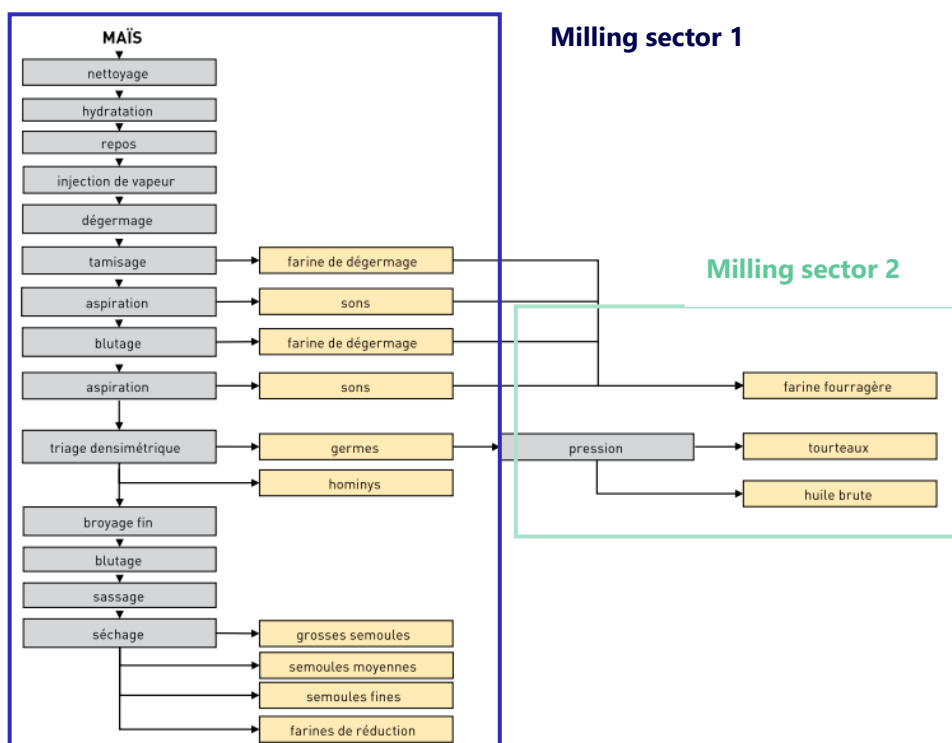
We harmonized the milling and starch sector scopes, by extending the starch sector lca data to the packaging step, the inventory data for packaging were extrapolated from "maize starch at packaging" data.

**Limitations:**

Due to a lack of data on packaging for the ethanol sector, the scope wasn't extended to packaging for this sector, this may lead to some inconsistencies, specifically when conducting a contribution analysis, nevertheless regarding the low mass flows transiting in this sector we are confident in the low significancy of the non-inclusion of packaging in the final sector and FSC impacts for climate change. This claim is not applicable for human toxicity indicators where the contribution of packaging is more significant<sup>54</sup>.

**Appendix 3 : Supplementary information's for the corn FCS**

In the MFA model the milling sector was divided into two categories, based on their processing step in the production chain, the first sector which have maize germs as an output and the second sector which is located a step downstream, using the maize germs to produce oil and maize meal for feedstuff. The process diagram below is based on the Reseda survey on by-products of the agrifood sectors (Idele, 2017).



**Limitations:**

The MFA model mixes wet and dry milling processes in the same sector (milling sector 1), while the lca data differentiate them with separate LCI. We didn't properly separate them based on mfa flows; therefore, we took the wet milling process as the impact LCA data for the whole sector.

<sup>54</sup> 20% to 40% of the toxicity impacts, based on milling and starch sectors.

**Datasets used:**

<b>FSC sectors</b>	<b>Agribalyse Dataset</b>
Crop production	Grain maize, average from 6 optimized case study, basis scenario, at farm gate F - FR
Milling sector 1	Customized data based on "Maize germ and degermed, wet, from wet milling, at plant" the crop production was excluded.
Milling sector 2	Customized data based on "Maize germ meal expeller, and crude maize germ oil" the crop production dataset and drying dataset was excluded
Starch sector	Customized data based on "Maize germ and degermed, wet, from wet milling, at plant" the crop production dataset was excluded.
Ethanol sector	Customized data based on "DDGS and Ethanol, from corn, at plant" the crop production dataset was excluded.
Long-term storage	Customized data based on "Maize grain dried, stored and transported" dataset. Crop production and drying process was excluded from the inventory.
<b>Imported products</b>	<b>Environmental footprint datasets</b>
Corn	Maize (corn grain) production; , at farm, technology mix, production mix, Location : UE28+, GLO
Corn gluten feed	Maize gluten feed; , at plant, from wet milling (gluten feed production, with drying), production mix,World
Maize germs	Maize germ, dried; , at plant, from wet milling, production mix,GLO

## Appendix 4 Supplementary information's for the oats FCS

<b>FSC sectors</b>	<b>Agribalyse Dataset</b>
Crop production	Oat grain, national average, animal feed, at farm gate
Long-term storage	Customized data based on "Maize grain dried, stored and transported" dataset. Crop production and drying process was excluded from the inventory.
<b>Imported products</b>	<b>Environmental footprint datasets</b>
Oats	Oat grain production; , at farm, technology mix, production mix,EU28+ (european average)

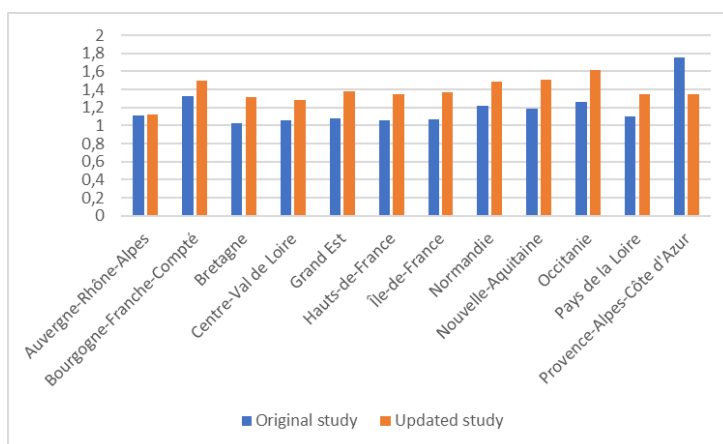
## Appendix 5 : Supplementary information's for the Dairy FCS

### National FCS:

For milk production we used the national average LCA data available in agribalyse 3.0.1, which represent a weighted average of the different production systems, differentiated by the type of feed (grass/ non grass etc.)

### Regional FCS:

The regional inventory data were based on an internal study conducted in 2019 by Desvaux Quentin<sup>55</sup>, the study aimed at producing a regionalised Life cycle inventories for milk production. The inventory data have been reproduced with updated and harmonised impact assessment method (EF 3.0), the original study was based on multiple Impact assessment methods, Recipe midpoint for climate change as an example. Below is the influence of the updated Impact assessment method on the regional carbon intensity of the production of 1kg of milk.



The average percentage change is 18.38%. Mainly due to different Characterisation factor for methane emissions (25 in original study, 34 in the EF3.0 method)

### The thermal process issue:

The biggest weakness of the dairy sector case study, is the representativeness of the milk thermal processing, the agribalyse dataset relies on pasteurisation thermal process as a proxy for Ultra-high temperature process, it appears that this type of treatment is not at all representative of the French market, which is dominated by the UHT type milk<sup>56</sup>. We can claim with high confidence that this distribution was similar in the reference year of the MFA study (2010). Djekick and colleagues (2013) studied the environmental impacts various dairy products in Slovakia, the Thermal energy Input range for the UHT milk was higher than the pasteurized one (62.5% to 230%) which may suggest a greater impact on climate change given that the source of this heat is fossil.

### Butter:

There are two types of butter, salted and unsalted, the latter accounts for the vast majority of sales hence the use of related LCA data as impacts data for the aggregated category "Butter".

We modified the initial data to be more representative of the French sector (essentially the electricity mix), see detailed changes below: Original data : "Butter, unsalted, at dairy (WFLDB 3.1)"

<sup>55</sup> The study is available upon request to the author or Jean-Yves courtonne.

<sup>56</sup> <https://www.agro-media.fr/analyse/le-marche-francais-domine-par-les-laits-uht-53918.html>

Initial Input data	New representative input data
market group for electricity, medium voltage - RER	Electricity, medium voltage {FR}  market for   Cut-off, S - Copied from Ecoinvent

### Yogurts:

Enhanced spatial resolution of the data inventory for yoghurt production dataset :

Original data : « yogurt production, from cow milk, CA-QC » data changes below

Initial Input data	New representative input data
Ammonia, liquid {RoW}  market for   Cut-off, S - Copied from Ecoinvent	Ammonia, liquid_steam reforming process_at plant_EU-28+3_S
Chemical factory, organics {GLO}  market for   Cut-off, S - Copied from Ecoinvent	Chemical factory, organics {RER}  construction   Cut-off, S - Copied from Ecoinvent
Electricity, medium voltage {CA-QC}  market for   Cut-off, S - Copied from Ecoinvent	Electricity, medium voltage {FR}  market for   Cut-off, S - Copied from Ecoinvent
Heat, district or industrial, natural gas {CA-QC}  market for   Cut-off, S - Copied from Ecoinvent	Heat, district or industrial, natural gas {Europe without Switzerland}  market for heat, district or industrial, natural gas   Cut-off, S - Copied from Ecoinvent
Hydrogen peroxide, without water, in 50% solution state {RoW}  market for hydrogen peroxide, without water, in 50% solution state   Cut-off, S - Copied from Ecoinvent	Hydrogen peroxide, without water, in 50% solution state {RER}  market for hydrogen peroxide, without water, in 50% solution state   Cut-off, S - Copied from Ecoinvent
Nitric acid, without water, in 50% solution state {RoW}  market for nitric acid, without water, in 50% solution state   Cut-off, S - Copied from Ecoinvent	Nitric acid, without water, in 50% solution state {RER}  market for nitric acid, without water, in 50% solution state   Cut-off, S - Copied from Ecoinvent
Propylene glycol, liquid {RoW}  market for propylene glycol, liquid   Cut-off, S - Copied from Ecoinvent	Propylene glycol, liquid {RER}  market for propylene glycol, liquid   Cut-off, S - Copied from Ecoinvent
Sodium hypochlorite, without water, in 15% solution state {RoW}  market for sodium hypochlorite, without water, in 15% solution state   Cut-off, S - Copied from Ecoinvent	Sodium hypochlorite, without water, in 15% solution state {RER}  market for sodium hypochlorite, without water, in 15% solution state   Cut-off, S - Copied from Ecoinvent
Sugar, from sugar beet {GLO}  market for   Cut-off, S - Copied from Ecoinvent Sugar, from sugarcane {GLO}  market for   Cut-off, S - Copied from Ecoinvent	Sugar, from sugar beet; _from sugar production_FR
Tap water {CA-QC}  market for   Cut-off, S - Copied from Ecoinvent	Tap water {Europe without Switzerland}  market for   Cut-off, S - Copied from Ecoinvent
Transport, freight, lorry, unspecified {RoW}  market for transport, freight, lorry, unspecified   Cut-off, S - Copied from Ecoinvent	Transport, freight, lorry, unspecified {RER}  market for transport, freight, lorry, unspecified   Cut-off, S - Copied from Ecoinvent
Water, deionised, from tap water, at user {RoW}  market for water, deionised, from tap water, at user   Cut-off, S - Copied from Ecoinvent	Water, deionised, from tap water, at user {CH}  market for water, deionised, from tap water, at user   Cut-off, S - Copied from Ecoinvent
Water, unspecified natural origin, CA	Water, unspecified natural origin, FR
Whey {GLO}  market for   Cut-off, S - Copied from Ecoinvent	Whey, at plant/FR U



### Assumptions:

For sugar, the type assumed to be added is 100% sugar beet type, regarding the lower costs of this type of sugar in France. And the production of sugar beet in France.

### LCA Data used :

Fsc sectors	Agribalyse
Milk production	Cow milk, national average, at farm gate/kg
Milk packaging	Milk, skimmed, UHT, processed in FR   Ambient (average)   HDPE   at packaging/ milk was excluded from the inventory
Milk skimming	Customized data based on "Liquid milk, whole milk, pasteurised, at dairy (WFLDB 3.1)" Milk production is excluded.
Butter production	Customized data based on "Butter, 82% fat, unsalted, processed in FR   Chilled   PP   at packaging", the butter production process data set was modified to be more representative of the French context.
Yogurts and Milk-based desserts	Based on "Yogurt production, from cow milk, CA-QC" the data was modified to comply with the French context.
Cheese production	Weighted average of soft cheese and hard cheese processes Soft cheese: Cheese production; from raw milk, soft cheese; French production mix, at plant; 1 kg of soft cheese (PGi) Hard cheese: Cheese production; from raw milk, Hard cheese; French production mix, at plant; 1 kg of hard cheese (PGi)
Whey powder production	Whey powder production, processing
Milk-cream packaging	Liquid cream 30% fat, UHT, processed in FR   Chilled   PP   at packaging / Cream was excluded from inventory
Milk powder production	Milk, powder, semi-skimmed, non-rehydrated, processed in FR   Ambient (average)   Cardboard   at packaging/ Milk production is excluded
Condensed milk production	Condensed milk, without sugar, whole, processed in FR   Ambient (average)   Steel   at packaging / Milk production was excluded