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APPLICATION AND REFINEMENT OF TERRITORIAL LIFE CYCLE ASSESSMENT TO THE CALCULATION OF THE CARBON FOOTPRINT AND THE NORMALIZATION FACTORS OF GALICIA

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Application and refinement of territorial Life Cycle Assessment to the calculation of the carbon footprint and the normalization factors of Galicia

Dna. Almudena Hospido Quintana

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Dra. Mª Asunción Antón Vallejo, Investigadora de Análisis de Ciclo de Vida y Agricultura, Institut de Recerca i Tecnologia Agroalimentàries (IRTA), Barcelona.

Dra. Mª Luz Loureiro García, Catedrática de Fundamentos de Análisis Económico, Universidade de Santiago de Compostela.

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Calificación: ***Sobresaliente Cum Laude.***

Abstract

The present thesis has been built around the territorial LCA framework, applying and improving this innovative methodology to obtain the carbon footprint and the normalisation factors of all Galician consumption and production activities. The location and characteristics of the region under study are presented first, followed by an overview of the LCA methodology, and more specifically of the territorial LCA approach. Then, several individual studies of Galician based products (either produced or consumed in the region) are presented, which are later on used to obtain the main outcomes and of this work, the Galician carbon footprint and normalisation factors. Last, ways forward to continue this project are presented, and conclusions are drawn based on the current results.

Galicia is an Autonomous Community located in the north west of Spain, having particular demographic, climatic and economic characteristics. The region had 2.718.525 inhabitants in 2017, very spread among the numerous villages existing in the territory. The Galician population is elderly and mainly rural. The Galician climatic conditions differ from those of Spain and are characterized by lower mean temperatures and higher precipitation rates than the country average. Being a rural area, the economic relevance of the primary sector is higher than in the rest of the country, mainly linked to the agriculture, livestock and fishing sector. Within the Galician secondary sector, the manufacturing industries stand out and, among them, food processing and vehicle manufacturing can be highlighted. Last, the tertiary sector is quite split among its numerous existing services in the region. The expenditures of the Galician inhabitants are lower than those of an average Spanish, and differently distributed: Galicians spend more money in food, and less in housing and leisure. Regarding tourism, the Galician visitors only represented 2% of the Spanish touristic overnights in 2016, but the regional touristic sector has been increasingly growing in the last few years. Being an Autonomous Community, the Galician government owns certain competencies, transferred from the Spanish central administration and, among them, environmental protection stands out. So, the Galician government can enforce measures to lower the environmental impacts in the area, which highlights the relevance of

the calculation of those impacts at a regional level, since policies aiming at their mitigation can be applied at the regional scale.

Life Cycle Assessment (LCA) is a methodology to assess the environmental impacts of a product, process or service throughout its entire life cycle, i.e. from the extraction of raw materials to the end of life. LCA studies consist of four stages:

i. Goal and scope definition, where the purpose of the study is set, its boundaries are defined and the functional unit is chosen (i.e. the reference to which the inputs and outputs of the system are related, and to which the environmental impacts will be referred).
ii. Inventory analysis, where inputs and outputs to characterise all stages of the life cycle are gathered, and which in turn can be conducted following three approaches:
    - A process analysis (PA) based approach, in which process flow diagrams are created to describe the system under study, showing the connections of the different processes of a product system, and ultimately linking the inventory data to the final product under assessment. This approach has traditionally been used to obtain the environmental impacts of individual products and processes.
    - An Input-Output (IO) based approach, in which IO matrixes containing the monetary interactions of a certain economy are linked to environmental data, which can be used to obtain the impacts of large scale systems such as countries. Two types of IO data exist: Single Region Input Output (SRIO) matrixes and Multi Region (MRIO) ones, being the latter more complex but also leading to more accurate results.
    - A hybrid approach, which combines both of them, benefiting from their advantages (i.e. the high level of detail of PA and the completeness of IO), and thus it is believed to be the most accurate one.
iii. Impact assessment, where inventory flows are converted into potential environmental impacts. This stage consists of several mandatory stages and some optional ones.
    - Mandatory stages:

        - Selection of impact categories, which can be chosen at the endpoint (damage) or midpoint (intermediate) level.
        - Classification or assignation of the inventory flows to each impact category.
        - Characterisation or conversion of the inventory flows into impacts by means of several multiplicators (i.e. characterisation factors).
    - Optional stages:
        - Normalisation, where the impacts of a particular product or service are compared to a certain reference, which usually corresponds to the annual impacts that occur in the region where the product is produced or consumed. This step can be used to identify inconsistencies in the impact results, to facilitate the communication of the results to non-experts and to ease decision making, and it can also serve as a first step before other optional phases.
        - Grouping, which consists on aggregating impact categories into several groups sharing certain characteristics.
        - Weighting, which expresses all normalised results into equivalent units, and may involve summing all the results into a single indicator
        - Data quality assessment, referring to any further analysis on data quality.

iv. Interpretation, where the findings of the previous stages are analysed together, and conclusions and recommendations are drawn.

A hybrid approach has been applied in this thesis, starting from the pure development of PA studies to finish with the application and refining of the Territorial LCA methodology. Regarding the impact assessment stage, two main impact categories have been used in most of the articles that compose this thesis: the Carbon Footprint (CF) and the Water Footprint (WF). The CF measures the total greenhouse gas (GHG) emissions throughout the life cycle of a product, expressed into CO_2 equivalents. The WF measures the potential environmental impacts related to water use, which can be evaluated through several approaches. Within the optional impact assessment stages, normalisation is also meaningful in this document.

The LCA framework, which was first conceived to calculate the environmental impacts of products or services, was later on adapted to apply to territories. Territorial LCA is a hybrid approach developed by Eleonore Loiseau and colleagues, which can be used to obtain the environmental impacts linked to all the consumption and production activities of a certain area. To obtain those impacts, both the consumption and the production activities are split into several subcategories (i.e. food, goods, services, housing and transport for consumption; primary sector, quarrying, energy, building, manufacturing activities, transport, services and end of life for production), for which inventories need to be obtained.

The territorial LCA approach has been used and adapted in this document, to calculate the carbon footprint of all Galician consumption and production activities, and also several other midpoint indicators, which are then the basis for the Galician normalisation factors calculation.

Thus, the first step to apply territorial LCA to Galicia was to gather inventory data of the consumption and production activities taking place within the area. Several LCA studies of individual products produced and consumed in Galicia were carried out within the framework of this thesis. The inventories and results of these PA based studies were used either to build the Galician inventories or to test the normalisation factors obtained. It should also be noticed that these first PA based studies of individual products were essential for the doctoral candidate to get familiar with the LCA framework, necessary for the subsequent deepening into IO and hybrid approaches.

Two LCA studies involving Galician products are shown first in this document, both of them linked to the traditionally relevant primary sector, and more specifically to livestock and fishing.

First, the environmental impacts of two Galician brands of milk were evaluated (**paper 1**), comparing a traditional brand to a novel premium one (Unicla), conceived to be have positive effects on consumer health. Unlike many other premium brands, Unicla was not obtained by enriching the final product, but in a natural way by improving the cows' diet. The premium diet provided to the Unicla cows was expected to lower their enteric GHG emissions, and thus the environmental burdens of the Unicla brand were also expected to be lower than those of conventional milk. To evaluate so, both brands were compared in terms of CF, WF and health effects, and it was found that the CF of Unicla was lower, that its WF was not significantly different from that of conventional milk, and that it could help protecting its consumers from cardiovascular diseases and oxidative damage, among other health benefits. A recent update this study led to the certification of the CF of both brands, and to the inclusion of the CF reduction percentage in the Unicla packaging. Unicla milk became the first product of the Spanish livestock sector to obtain such certification, and to use that type of environmental labelling.

A second study (**paper 2**) evaluated the CF of canned tuna manufactured by a Galician company in 2014. The study was an update of a previous one from 2005, and it aimed at evaluating how the GHG emissions had evolved due to the changes in the raw material provision and production processes. It was found that the CF of the new supply chain was slightly lower than that of the previous one, and that fishing and processing were the main contributors to the GHG emissions. Once the CF of the yearly production of the company was obtained, the effects that compensating it through afforestation could have on water sarcity were evaluated. A simplified approach was followed to calculate the WF of the compensation project, and it was proven that this indicator could be useful to choose the most suitable location for afforestation, even though it was acknowledged that the approach still needs to be further refined.

Inventory data from both milk and canned tuna studies, being both of them Galician products, were used at later stages of the thesis when the impacts of the Galician production were evaluated. More specifically, the raw milk inventory data (and some crop production inventories from that study) were used as part of the Galician production inventories, and the canned tuna results were used to verify the robustness and applicability of the corresponding Galician normalisation factors.

The environmental performance of an imported product consumed in Galicia was also evaluated: the Ecuadorian banana, the second most consumed fruit in the region. Being an imported product from overseas, and also an agricultural based food commodity, the environmental degradation linked to its consumption was expected to be very meaningful. Thus, on a first study (**paper 3**), the CF of organic and conventional banana consumption in Spain was evaluated. Several efforts were made to obtain as precise impacts as possible: the nitrogen emission factors arising from fertilised soils were adapted to the Ecuadorian climatic conditions, and modifications were made to consider different transport characteristics (refrigeration, different load factors). The CF results of that study were then completed in a second one (**paper 4**), where WF and economic value were calculated throughout the entire banana life cycle, so as to obtain a complete picture of how the impacts and the price of the product evolve through the different stages from production to consumption. It was concluded that the CF of organic banana was lower than that of conventional ones, while the opposite was found for the WF indicator. The farm system was the stage that contributed the most to both impacts, and it was also found that its economic value was less important than that of most of the remaining stages, showing that wealth distribution along the value chain is still unfair for the farmers. The complete LCA results of both types of banana were also used to test the robustness and applicability of the normalisation factors of the Galician consumption.

After these first LCA studies of Galician based products, an approach based on territorial LCA was used to obtain the CF of all Galician consumption and production activities (**paper 5**). To do so, activity descriptors were combined with inventory data to build Galician consumption and production inventories. Two types of activity descriptors were used: physical flows (such as the amount of electricity consumed in households or the annual output of raw milk produced in the region) and economic ones (such as the annual expenditure of the inhabitants on a certain food commodity or the annual economic output of a certain product manufactured in the territory). The former were combined with PA databases such as Ecoinvent, and the latter with IO data from the USEIO database[1]. This database reflects the structure and emissions of the United States, and thus it does not accurately reflect the Galician impacts, but it was chosen both here and in the original territorial LCA applications due

[1] USEIO: United States Environmentally extended Input Output database.

to its completeness (in terms of environmental flows and activities) and simplicity of application (it is implemented in some LCA softwares such as SimaPro). When applying territorial LCA to a region having a certain degree of self-sufficiency, such as Galicia, double counting issues appeared: being territorial LCA a life cycle based methodology, the impacts of a Galician product include all life cycle burdens, not only those happening in Galicia. Thus, if the product is used again as a raw material in a different Galician industry, its impacts would be accounted for twice. A procedure to avoid this double counting, *intra* double counting, was defined and implemented. This procedure follows a consumer responsibility approach (i.e. the activities far downstream in the supply chain bear the largest share of the impacts) based on economic data of the Galician inter-industry flows, taken from the Galician Input Output matrix. Once the CF of all Galician consumption and production activities was calculated, hotspots were identified (i.e. electricity, heating and animal based food products in consumption and electricity and food manufacturing in production) and suggestions were made to lower the GHG emissions of both the Galician consumption (installation of solar panels and lowering the consumption of livestock-based foodstuff) and production (shifting to more renewable sources of electricity and lowering livestock emissions). The main limitations of the procedure to calculate the CF were also acknowledged: data gaps, long time consumption requirements to compile PA based inventories, and the low representativeness of the USEIO database.

Once these first CF results were obtained, an attempt was made to refine them (**paper 6**), also aiming at the simplification of the methodology for future CF calculations in this or other regions. Thus, the aforementioned results were split into PA based results and USEIO based ones, and they were compared to those obtained with other IO based approaches, including both SRIO and MRIO data. Among the IO databases used, the Galician IO matrix (SRIO), the World Input Output database (MRIO) and the Exiobase database (MRIO) were compared. Different assumptions were required when applying each approach, looking for their simplification, and the CF results obtained were compared to each other. It was concluded that the Galician IO matrix was the best option to obtain reliable CF results with low calculation efforts, and that this approach could be used for subsequent, simplified territorial LCA studies in this or other regions where IO tables are available. The CF results obtained with that matrix did not differ much from those obtained in the previous study, even though they were differently split into activities. It was also acknowledged that this new approach could still be improved, since a SRIO matrix had been used (which probably leads to the underestimation of the CFs) and some further assumptions were required.

Last, the inventory data obtained in the Galician CF study was used again to calculate the Normalisation Factors (NFs) of the consumption and production activities in the region (**paper 7**). The study was, to the best of our knowledge, the first application of the territorial LCA approach to calculate normalisation references, and also the first calculation of those references at the subnational level. Fifteen NFs for the Galician consumption and production were made available, which were split into its main contributing activities and substances. Since in practice NFs are the annual impacts of consumption and production activities, the results obtained were also used to identify environmental hotspots and to propose mitigation actions. The hotspots found were consistent to those already found for the Galician CF, and thus the mitigation measures pointed in the same direction. Both Galician normalisation datasets were tested in the two comparative case studies included in this thesis: the production NFs were used to evaluate the impacts of the former and the current canned tuna supply chain, and the consumption NFs were applied to the impact results of conventional and organic banana consumption. The normalised results obtained using the Galician NFs were compared to those calculated with different reference systems, and some differences were found in the relevance of the impact categories, even though they did not significantly alter the conclusions of the case studies. The results point at the usefulness of these additional normalisation references, so as to allow conducting sensitivity analysis in LCA studies and to test the robustness of their conclusions. It was also acknowledged that the methodology still had several drawbacks: apart from those already mentioned for the CF determination, several other sources of uncertainty were identified when calculating the remaining NFs: the lack of substances in the inventory data, the uncertainty of the characterisation factors and the inconsistencies found between the USEIO and the PA based inventories. Thus, it was concluded that territorial LCA is a promising approach for the determining of NFs, but that some improvements could still be made to the procedure.

Territorial LCA can be considered an iterative approach, in which, once the first results are computed, they can be refined by using more detailed or representative inventory data. With this in mind, several possible ways forward to improve the current results have been proposed:

- The substitution of the USEIO based inventories by MRIO data (ideally Galician based).
- The improvement of the current PA based inventories, either by updating the existing Galician inventories or by substituting the generic ones (from Ecoinvent) by regional specific ones.
- The use of PA data to model those activities which have been so far characterised using the USEIO database
- The distinction between on-site and off-site impacts, which could lead to more effective decision making.

It can be concluded that this thesis successfully applied and refined a procedure based on territorial LCA to calculate the normalisation factors of all Galician consumption and production activities, in the first application of the approach to obtain normalisation factors. These Galician NFs, being calculated following a life cycle approach, are expected to be more consistent with the reference systems used in LCA studies of individual products. A double counting solving procedure has been proposed to allow applying territorial LCA to regions in which production activities are linked to each other, based on IO tables. Special attention has been paid to the CF results, for which different calculation methodologies were compared, seeking both to improve their reliability and to simplify the calculation procedures. An approach based on the Galician IO matrix was suggested to obtaining reliable, quick CF results for Galicia or other regions having IO tables.

Last, it was also found out that the water footprint indicator can be used to choose among locations for afforestation projects. This was stated through a very simple approach, which should be better refined to allow for a more reliable calculation of evapotranspiration values.

Moreover, several procedures to refine the nitrogen emissions from fertilisation in tropical countries and to account for different load factors in transport systems have been proposed as improvements on the computation of environmental impacts for PA based LCA.

In summary, this doctoral thesis contributed both to the further refinement of PA based LCA studies, by providing suggestions to better account for the emissions linked to fertilisation and transport; and to hybrid ones, by proposing an approach to avoid double counting in regions where IO tables are available and by testing alternatives to the USEIO database when calculating CF using territorial LCA. Moreover, a procedure was proposed to evaluate how afforestation projects could affect water scarcity, which could be used to choose among different locations for GHG compensation projects.

Resumen

Esta tesis se ha desarrollado en el marco del Análisis de Ciclo de Vida (ACV) territorial, aplicando y mejorando esta metodología innovadora para obtener la huella de carbono y los factores de normalización de todas las actividades de consumo y de producción gallegas. La ubicación y las características de la región en estudio se presentan primero, seguidas de una descripción general de la metodología de ACV, y más específicamente del ACV territorial. A continuación, se presentan varios estudios individuales de productos gallegos (ya sean producidos o consumidos en la región), que luego se utilizan para obtener los principales resultados de este trabajo: la huella de carbono y los factores de normalización de Galicia. Por último, se presentan los pasos a seguir para la continuación de este proyecto, y se extraen conclusiones en base a los resultados actuales.

Galicia es una comunidad autónoma ubicada en el noroeste de España, con características demográficas, climáticas y económicas particulares. La región tenía 2.718.525 habitantes en 2017, muy repartidos entre los numerosos municipios existentes en el territorio. La población gallega es mayoritariamente rural y está significativamente envejecida. Las condiciones climáticas de la región difieren de las de España y se caracterizan por temperaturas medias más bajas y mayores tasas de precipitación que el promedio del país. Al ser un área rural, la relevancia económica del sector primario es mayor que en el resto del país, principalmente vinculada al sector agrícola, ganadero y pesquero. Dentro del sector secundario gallego, destacan las industrias manufactureras y, entre ellas, el procesado de alimentos y la fabricación de vehículos. Por último, el sector terciario está bastante dividido entre los numerosos servicios existentes en la región. Los gastos de los habitantes de Galicia son menores que los de un español promedio y se distribuyen de manera diferente: los gallegos gastan más dinero en comida, y menos en vivienda y ocio. En cuanto al turismo, los visitantes gallegos solo representaron el 2% de las visitas turísticas a España en 2016, pero el sector turístico regional ha crecido significativamente en los últimos años. Al igual que el resto de las comunidades autónomas, el Gobierno de Galicia posee ciertas competencias, transferidas desde el gobierno central, entre las que destaca la protección ambiental. Por lo tanto, el gobierno

regional tiene la potestad de aplicar medidas para la reducción de los impactos ambientales en el área, lo que resalta la relevancia del cálculo de esos impactos a nivel regional, puesto que las políticas encaminadas a su mitigación se pueden aplicar a escala gallega.

El ACV es una metodología para la evaluación de los impactos ambientales de un producto, proceso o servicio a lo largo de todo su ciclo de vida, es decir, desde la extracción de las materias primas hasta su fin de vida. Los estudios de ACV constan de cuatro etapas:

i. Definición de objetivos y alcance, en la que se establecen los objetivos del análisis, los límites del sistema y la unidad funcional (la referencia con la que se relacionan las entradas y salidas del sistema, y a la que se referirán los impactos ambientales).
ii. Análisis de inventario, en la que se recopilan los flujos de entrada y salida que tienen lugar en todas las etapas del ciclo de vida, y que a su vez se puede realizar siguiendo tres enfoques:
    - El Análisis de ciclo de vida de Procesos (AP), en el que se crean diagramas de flujo para describir el sistema en estudio, y que ilustran las conexiones entre las distintas etapas de un ciclo de vida, y en el que se vinculan los datos de inventario al producto final en estudio. Este enfoque se ha usado tradicionalmente en el análisis ambiental de productos y procesos individuales.
    - El enfoque Input-Output (IO), en el que las matrices IO que contienen los flujos monetarios de una determinada economía se vinculan a datos ambientales, y que se utilizan para obtener los impactos de sistemas a gran escala, como los países. Existen dos tipos de datos de IO: las matrices que contienen datos de una sola región (SRIO por sus siglas en inglés), o las de múltiples regiones (MRIO), siendo estas últimas más complejas pero dando lugar a resultados más precisos.
    - Un enfoque híbrido, que combina los anteriores beneficiándose de sus ventajas (es decir, el alto nivel de detalle de AP y la visión global del IO), y que se considera más preciso.

iii. Evaluación de impacto, en la que los flujos de inventario se convierten en impactos ambientales potenciales. Esta etapa consta de varios elementos obligatorios y algunos opcionales.
   - Elementos obligatorios:
     - Selección de categorías de impacto, que pueden elegirse en el punto final (daños a los ecosistemas, la salud humana o los recursos) o en un punto medio (entre la emisión o consumo de la sustancia y el daño).
     - Clasificación, o asignación de los flujos de inventario a cada categoría de impacto.
     - Caracterización, o conversión de los flujos de inventario en impactos, mediante una serie multiplicadores, llamados factores de caracterización.
   - Elementos opcionales:
     - Normalización, en la los impactos de un producto o servicio concreto se comparan con una cierta información de referencia, que generalmente corresponde a los impactos anuales que ocurren en la región donde se produce o consume el producto. Este paso puede usarse para identificar inconsistencias en los resultados de impacto, para facilitar la comunicación de los resultados a personas no expertas y para facilitar la toma de decisiones, y que también puede servir como un primer paso antes de alguna de las otras fases opcionales.
     - Agrupación, en la que los resultados de las distintas categorías de impacto se agrupan de acuerdo a ciertas características comunes.
     - Ponderación, que expresa los resultados normalizados en unidades equivalentes, y que puede implicar la suma de todos los resultados en un solo indicador.
     - Análisis de calidad de los datos, referido a cualquier análisis adicional de la calidad de los datos.

iv. Interpretación, en la que los hallazgos de las etapas previas se analizan en conjunto, y se extraen conclusiones y recomendaciones.

En esta tesis se ha aplicado un enfoque híbrido, partiendo del desarrollo de estudios de AP para finalizar con la aplicación y el perfeccionamiento de la metodología de ACV territorial. Con respecto a la etapa de evaluación de impacto, se han utilizado dos categorías principales de impacto en la mayoría de los artículos que componen esta tesis: la huella de carbono (HC) y la huella hídrica (HH). La HC mide las emisiones totales de Gases de Efecto Invernadero (GEI) a lo largo de todo el ciclo de vida de un producto, expresadas en unidades de CO_2 equivalente. La HH mide los posibles impactos ambientales relacionados con el uso del agua, que pueden evaluarse a través de varios enfoques. Dentro de las etapas opcionales de evaluación de impacto, la normalización también tiene un peso significativo en este documento.

El marco del ACV, concebido inicialmente para calcular los impactos ambientales de productos o servicios, se adaptó posteriormente para aplicarse al análisis ambiental de territorios. El ACV territorial es una metodología híbrida desarrollada por Eléonore Loiseau y sus colaboradores, que se puede utilizar para obtener los impactos ambientales ligados a todas las actividades de consumo y producción de un área determinada. Para obtener esos impactos, tanto las actividades de consumo como las de producción se dividen en varias subcategorías (alimentos, bienes, servicios, vivienda y transporte para el consumo, y sector primario, minería, energía, construcción, industria, transporte, servicios y fin de vida para producción), para las cuales es necesario obtener datos de inventario.

La metodología de ACV territorial se ha empleado y adaptado en este documento para el cálculo de la huella de carbono de todas las actividades de consumo y producción gallegas, y también para el de otros indicadores de punto medio, que son la base del cálculo de los factores de normalización gallegos.

Por lo tanto, el primer paso para aplicar el ACV territorial a Galicia fue la recopilación datos de inventario de las actividades de consumo y producción que tienen lugar en la región. En el marco de esta tesis, se han llevado a cabo varios estudios de ACV de productos individuales producidos y consumidos en Galicia. Los datos de inventario inventarios y los resultados de estos estudios basados en AP se han utilizado para la construcción de los inventarios de Galicia o para la comprobación de los factores de normalización obtenidos. Cabe destacar también que estos primeros estudios basados en el AP de productos individuales han sido esenciales para que la candidata al doctorado se familiarizase con el marco del ACV, como primer paso necesario para la posterior profundización en enfoques IO e híbridos.

Tras una introducción sobre la metodología empleada y las características de Galicia, la tesis se inicia con dos estudios de ACV de productos gallegos, ambos vinculados al sector primario, tradicionalmente relevante en la región, y más específicamente a los sectores ganadero y pesquero.

En primer lugar, se evaluaron los impactos ambientales de dos marcas de leche gallegas (**artículo 1**), comparando una marca tradicional con una novedosa marca premium (Unicla), concebida para tener efectos positivos en la salud de sus consumidores. A diferencia de muchas otras marcas premium, Unicla no se obtiene enriqueciendo el producto final, sino de forma natural al mejorar la dieta de las vacas. Dado que se esperaba que la dieta premium proporcionada a las vacas Unicla redujese sus emisiones entéricas de GEI, era también de esperar que los impactos ambientales de la marca Unicla fueran menores que las de la leche convencional. Para evaluarlo, se compararon ambas marcas en términos de HC, HH y efectos sobre la salud, y se encontró que la HC de Unicla era más baja, que su HH no era significativamente diferente de convencional, y que podría ayudar a proteger a sus consumidores contra enfermedades cardiovasculares y daño oxidativo, entre otros beneficios para la salud. Una actualización reciente de este estudio condujo a la certificación de la HC de ambas marcas, y a la inclusión de la reducción porcentual de la HC en el embalaje de Unicla. La leche de Unicla se convirtió así en el primer producto del sector ganadero español en obtener dicha certificación y en utilizar ese tipo de etiquetado ambiental.

Un segundo estudio (**artículo 2**) evaluó la HC del atún en conserva fabricado por una empresa gallega en 2014. El estudio era una actualización de uno anterior de 2005, y tenía como objetivo evaluar cómo habían evolucionado las emisiones de GEI debido a los cambios en los procesos de producción y en la provisión de materias primas. Se descubrió que la HC de la nueva cadena de suministro era levemente inferior a la de la anterior, y que la pesca y el procesado eran los principales contribuyentes a las emisiones de GEI. Una vez obtenida la HC de la producción anual de la compañía, se evaluaron los efectos que su compensación, a través de un proyecto de forestación, podría tener sobre la escasez hídrica. Se empleó un enfoque simplificado para calcular la HH del proyecto de compensación, y se demostró que este indicador podría ser útil para elegir la ubicación más adecuada para la forestación, si bien todavía es necesario perfeccionar el enfoque empleado.

Los datos de inventario de los estudios de leche y atún en conserva, ambos productos gallegos, se utilizaron en etapas posteriores de la tesis, cuando se evaluaron los impactos de la producción en Galicia. Más específicamente, los datos de inventario de leche cruda (y algunos inventarios de producción de cultivos de ese estudio) se utilizaron como parte de los inventarios de producción gallegos, y los resultados del atún enlatado se usaron para verificar la solidez y aplicabilidad de los factores de normalización de la producción de Galicia.

Se evaluó asimismo el desempeño ambiental de un producto de importación consumido en Galicia: el banano ecuatoriano, la segunda fruta más consumida en la región. Al ser un producto importado del exterior, y un producto alimenticio de base agrícola, se esperaba que la degradación ambiental vinculada a su consumo fuese muy significativa. Por lo tanto, en un primer estudio (**artículo 3**), se evaluó la HC del consumo de banano orgánico y convencional en España. Se procure que los impactos obtenidos fuesen lo más precisos posible, para lo que los factores de emisión de nitrógeno procedente de suelos fertilizados se adaptaron a las condiciones climáticas de Ecuador y se realizaron modificaciones para considerar diferentes características de transporte (refrigeración, diferentes porcentajes de carga). Los resultados de HC de ese estudio se completaron en un Segundo análisis (**artículo 4**), donde la HH y el valor económico del banana se calcularon a lo largo de todo su ciclo de vida, para obtener una visión holística de cómo los impactos y el precio del producto evolucionan a través de las diferentes etapas, desde la producción hasta el consumo. Se concluyó que la HC del banano orgánico era menor que la de los convencionales, si bien que la HH mostró resultados contrarios. La plantación es la etapa que más contribuye a ambos impactos, y sin embargo su valor económico es menor que el de la mayoría de las etapas restantes, mostrando que la distribución de riqueza a lo largo de la cadena de valor sigue siendo injusta para los agricultores. Los resultados completos de ACV de ambos tipos de banano también se utilizaron para evaluar la solidez y la aplicabilidad de los factores de normalización del consumo gallego.

Después de estos primeros estudios ACV de productos relacionados con Galicia, se utilizó un enfoque basado en el ACV territorial para obtener la HC de todas las actividades de consumo y producción de Galicia (**artículo 5**). Para ello, se combinaron descriptores de actividad con datos de inventario, para construir inventarios de consumo y producción en Galicia. Se utilizaron dos tipos de descriptores de actividad: flujos físicos (como la cantidad de electricidad consumida en los hogares o la producción anual de leche cruda producida en la región) y económicos (como el gasto anual de los habitantes en un determinado producto alimenticio o la producción económica anual de un determinado producto fabricado en el territorio). Los primeros se combinaron con bases de datos de AP como Ecoinvent, y los segundos con datos de IO como la base de datos USEIO[1]. Esta base de datos refleja la estructura y emisiones de los Estados Unidos, y por lo tanto no representa con exactitud los impactos gallegos, pero se ha elegido tanto en este estudio como en las primeras aplicaciones del ACV territorial por ser muy completa (en términos de flujos ambientales y actividades) y por la simplicidad de su aplicación (al estar implementada en algunos softwares de ACV como SimaPro). Al aplicar el ACV territorial a una región como Galicia, que posee un cierto grado de autosuficiencia, aparecieron problemas de doble conteo de los impactos: siendo el ACV territorial una metodología basada en el ciclo de vida, los impactos de un producto gallego incluyen todos los de su ciclo de vida, y no solo los de aquellas etapas que ocurren en Galicia. Por lo tanto, si el producto se utiliza nuevamente como materia prima en otra industria gallega, sus impactos se contabilizarían dos veces. Se concibió e implementó un procedimiento para evitar este doble conteo, denominado *intra double counting* en este documento. El procedimiento sigue un enfoque que asigna las responsabilidades ambientales al consumidor (es decir, las actividades situadas aguas

[1] USEIO: Base de datos Input Output ambiental de los Estados Unidos.

abajo en la cadena de suministro son responsables de la mayor parte de los impactos), en base a los datos económicos de los flujos interindustriales gallegos, tomados de la matriz IO de Galicia. Una vez calculadas las HCs de todas las actividades de consumo y producción gallegas, se identificaron aquellas de mayor impacto (electricidad, calefacción y alimentos de origen animal en consumo, y electricidad y fabricación de alimentos en producción) y se hicieron sugerencias para reducir las emisiones de GEI tanto del consumo gallego (instalación de paneles solares y reducción del consumo de productos alimenticios de origen animal) como de la producción (cambio a fuentes más renovables de electricidad y reducción de las emisiones del sector ganadero). Se identificaron asimismo las principales limitaciones del procedimiento seguido en el cálculo de la HC: la falta de datos, la gran inversión de tiempo requerida para compilar los inventarios basados en AP y la baja representatividad de la base de datos USEIO).

Una vez que obtenidos estos primeros resultados de HC, se intentó refinarlos, buscando asimismo la simplificación de la metodología para futuros cálculos de HC en esta u otras regiones (**artículo 6**). Así, los resultados antes mencionados se dividieron en los basados en PA y en USEIO, y se compararon con los obtenidos con otros enfoques IO, tanto de tipo SRIO como MRIO. Entre las bases de datos de IO utilizadas, se empleó la matriz IO de Galicia (SRIO), la base de datos World Input Output (MRIO) y la base de datos Exiobase (MRIO). Cada enfoque implicó una serie de asunciones que facilitasen su aplicación, y los resultados de HC obtenidos con cada uno de ellos se compararon entre sí. Se concluyó que la matriz IO de Galicia era la mejor opción para obtener resultados fiables de HC que no requiriesen largos procedimientos de cálculo, y que este enfoque podría utilizarse en estudios simplificados de ACV territorial, realizados posteriormente en Galicia o en otras regiones donde este tipo de tablas estén disponibles. Los resultados de HC obtenidos con esa matriz no difirieron mucho de los obtenidos en el estudio anterior, aunque su división en actividades sí fue diferente. Se señaló asimismo que este nuevo enfoque podría mejorarse aún más, ya que se empleó una matriz SRIO (que probablemente lleva a subestimar los valores de HC) y fueron necesarias algunas asunciones adicionales.

Por último, los datos de inventario obtenidos en el estudio de HC de Galicia se utilizaron nuevamente para calcular los Factores de Normalización (FN) de las actividades de consumo y producción de la región (**artículo 7**). El estudio fue, a nuestro entender, la primera aplicación del enfoque de ACV territorial al cálculo de referencias de normalización, y también el primer cálculo de dichas referencias a un nivel subnacional. Se obtuvieron quince FNs para el consumo y la producción de Galicia, que se dividieron en sus principales actividades y sustancias contribuyentes. Dado que en la práctica los FNs son los impactos anuales de las actividades de consumo y producción, los resultados obtenidos también se utilizaron para identificar puntos críticos ambientales y proponer acciones de mitigación. Dichos puntos críticos fueron consistentes con los que ya se habían identificado para la HC de Galicia y, por lo tanto, las medidas de mitigación apuntaban en la misma dirección. Ambos conjuntos de FNs gallegos se pusieron a prueba en los dos casos de estudios comparativos incluidos en esta tesis: los FNs de producción se utilizaron para evaluar los impactos de las dos cadenas de suministro del atún enlatado (la antigua y la actual), y los FNs de consumo se aplicaron a los resultados de impacto del consumo de banano orgánico y convencional. Los resultados normalizados obtenidos utilizando los FNs gallegos se compararon con los calculados con otros sistemas de referencia, y se encontraron algunas diferencias en la relevancia de las categorías de impacto, pese a que las conclusiones de ambos casos de estudio no variaron de forma significativa. Los resultados apuntan a la utilidad de estas referencias adicionales de normalización, que permitirán realizar análisis de sensibilidad en los estudios de ACV y probar la solidez de sus conclusiones. Además de los inconvenientes ya mencionados para la determinación de HC, se identificaron otras fuentes de incertidumbre al calcular los restantes FNs: la falta de sustancias en los datos de inventario, la incertidumbre de los factores de caracterización y las inconsistencias encontradas entre los inventarios basados en USEIO y en AP. Por lo tanto, se concluyó que el ACV territorial es un enfoque prometedor para la determinación de FNs, pero que aún se pueden hacer algunas mejoras al procedimiento.

El ACV territorial puede considerarse un enfoque iterativo en el que, una vez que se computan los primeros resultados, estos pueden refinarse mediante el uso de datos de inventario más detallados o representativos. Con esto en mente, se han propuesto varias formas posibles de mejorar los resultados actuales:

- La sustitución de los inventarios basados en USEIO por datos MRIO (idealmente basados en Galicia).
- La mejora de los inventarios actuales basados en AP, ya sea actualizando los inventarios gallegos existentes o sustituyendo los genéricos (de Ecoinvent) por específicos de la región.
- El uso de datos basados en AP para el modelado de aquellas actividades que hasta ahora se han caracterizado utilizando la base de datos USEIO.
- La distinción entre los impactos que tienen lugar en territorio gallego y fuera de él, y que podría conducir a una toma de decisiones más efectiva.

Se puede concluir que en esta tesis se ha aplicado y refinado con éxito un procedimiento basado en el ACV territorial para calcular los factores de normalización de todas las actividades de consumo y producción gallegas, en la primera aplicación de este enfoque a la obtención de factores de normalización. Se espera que estos FNs de Galicia, que se calculan siguiendo un enfoque de ciclo de vida, sean más consistentes con los sistemas de referencia utilizados en los estudios de ACV de productos individuales. Se ha propuesto un procedimiento de resolución del doble conteo que permita la aplicación de ACV territorial a regiones en las que las actividades de producción estén vinculadas entre sí, en base a tablas IO. Se ha prestado especial atención a los resultados de HC, para los cuales se han comparado diferentes metodologías de cálculo, buscando tanto mejorar su fiabilidad como simplificar los procedimientos de cálculo. Se ha sugerido un enfoque basado en la matriz de IO de Galicia para obtener resultados fiables y rápidos de HC para Galicia u otras regiones con tablas IO.

Por último, se ha descubierto también que la huella hídrica se puede utilizar para elegir entre ubicaciones para proyectos de forestación. Esto se ha comprobado en base a un enfoque muy simple, que debería ser refinado para permitir un cálculo más fiable de los valores de evapotranspiración. Asimismo, se han propuesto procedimientos para refinar el cálculo de las emisiones de nitrógeno de la fertilización en países tropicales, y para tener en cuenta diferentes factores de carga en sistemas de transporte, que servirán para mejorar el cálculo de los en los estudios de ACV basados en AP.

En resumen, esta tesis doctoral ha contribuido tanto al refinamiento de los estudios de ACV basados en AP, al proporcionar sugerencias para una mejor contabilización de las emisiones de la fertilización y el transporte; como al de los híbridos, proponiendo un enfoque para evitar el conteo doble en las regiones donde existen tablas IO y probando alternativas a la base de datos USEIO en el cálculo de HCs empleando ACV territorial. Además, se ha sugerido un procedimiento para evaluar cómo los proyectos de forestación podrían afectar la escasez hídrica, que podría utilizarse para elegir entre diferentes ubicaciones para proyectos de compensación de GEI.

Contents

Section 1: Introduction and objectives

Chapter 1: Life Cycle Assessment

This chapter describes the Life Cycle Assessment methodology, detailing its usefulness and applicability, and its required steps. Within that general description, emphasis is placed on the calculation of the carbon and water footprint indicators, and in the normalisation step. Then, focus is put on the territorial Life Cycle Assessment methodology, an application of the life cycle approach to the environmental assessment of territories, which has been used (and refined) here to calculate both the Galician carbon footprint and its normalisation factors.

1.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool to assess the environmental impacts associated with a product, process or service throughout its entire life cycle, from raw material acquisition to production, use, and final disposal (ISO, 14040:2006).

The origin and development of LCA responds to an increased awareness about the impacts of human activities in the environment, which lead to the development of methods to better understand and address these impacts. Among other purposes, LCA can assist in (ISO, 14044:2006):

— Identifying opportunities to improve the environmental performance of products at various points in their life cycle,

— Informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),

— Selecting relevant indicators of environmental performance, including measurement techniques

— Marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

LCA studies consist of four stages (Figure 1), which are further detailed in subsequent sections:

1. Goal and scope definition,
2. Inventory analysis,
3. Impact assessment,
4. Interpretation.

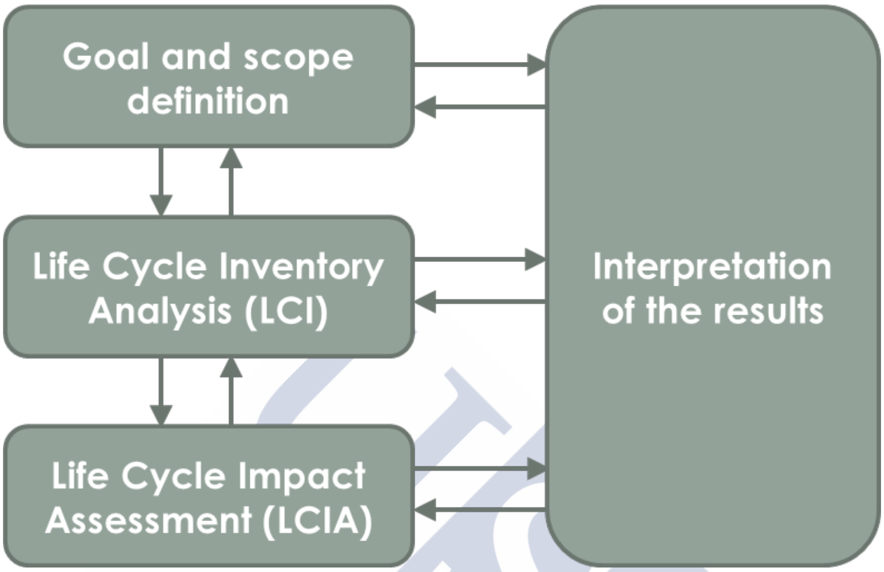

Figure 1: Stages of the Life Cycle Assessment. Adapted from ISO (14040:2006)

1.1.1 Goal and scope definition

In this first step, the purpose of the study is defined depending on the information that is required from it.

The goal of a LCA study includes its intended application, the reasons for carrying it out, the planned audience (to whom the results of the study are communicated), and whether the results are intended to be used in comparative assertions.

The scope includes, among others, the definition of the system to be studied and its boundaries and the functional unit (FU), which quantifies the function of the system under study, being a reference to which the inputs and outputs of the system are related, and to which the environmental impacts will be referred.

The system boundaries define the processes to be included in the study (Figure 2). Even though by definition an LCA should include all the stages of the life cycle of a product, process or service, i.e. a cradle to grave approach, other types of analysis can be performed depending on the objectives of the study: a cradle to gate approach, in which the analysis ends up at the factory gate, or a gate to gate approach, in which only one step of the value chain is evaluated (e.g., the manufacturing stage).

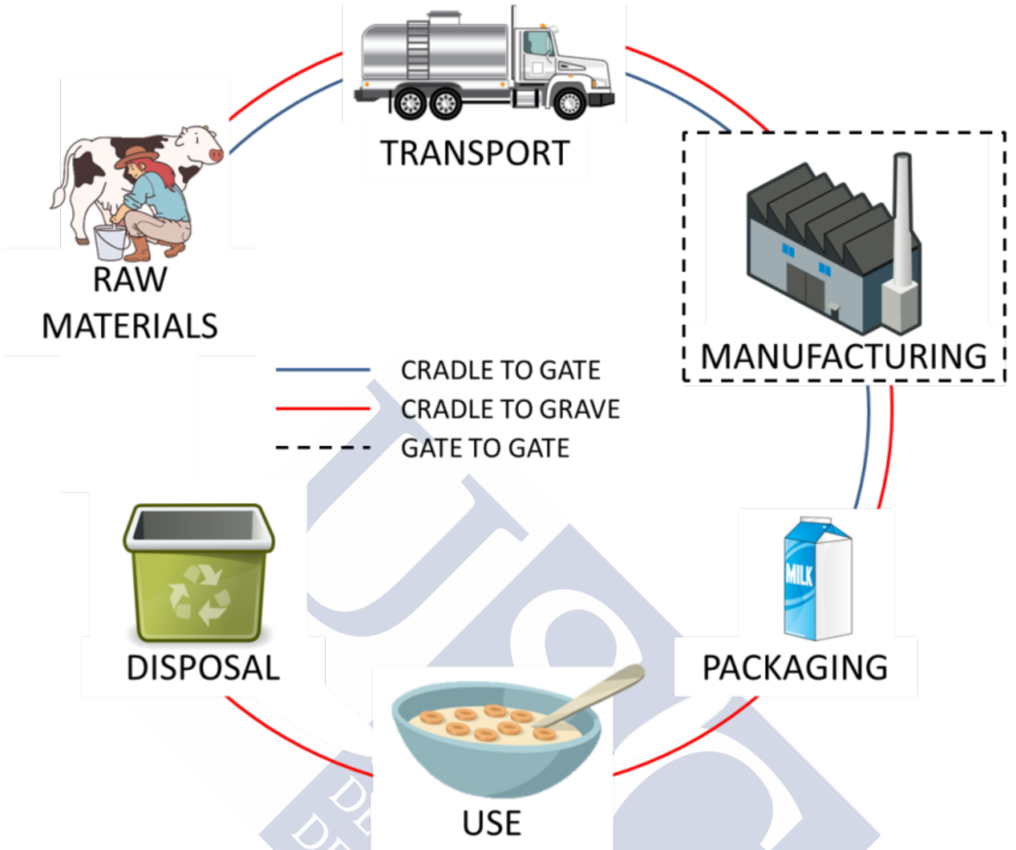

Figure 2: Description of the main approaches (and phases) considered in LCA studies (Hospido and Roibás, 2017).

Two major types of LCA studies exist, attributional and consequential. The former describes the environmental impacts linked to a certain functional unit, while the latter estimates how these impacts change in response to a change in the level of the functional units produced (Rebitzer et al., 2004).

1.1.2 Life Cycle Inventory Analysis

This step involves the quantification of inputs and outputs for the product, process or service throughout its life cycle. As a result of this step, the different stages included in the system boundaries, the resources consumed and the pollutants released, are linked by means of inventory tables.

Three main approaches can be followed to obtain life cycle inventories (Suh and Huppes, 2005):

i. a process analysis (PA) based approach (or bottom-up strategy)

ii. an Input-Output (IO) based approach (or top-down strategy)

iii. a hybrid approach, which combines both.

The main features of each approach are further detailed below:

Process Analysis (PA)

When PA is used, process flow diagrams are created to describe the system under study, showing the connections of the different processes of a product system, and ultimately linking the inventory data to the final product under assessment. When this approach is followed, some of the processes of the life cycle are unavoidably left out of the assessment (cut-off), due to the impossibility of gathering inventory data for all upstream (and downstream) steps of a certain production process. Thus, inventory data are obtained only for those stages that are expected to contribute the most to the final environmental impacts, while other stages are left out of the assessment, since it is assumed that the addition of successive upstream production stages has a small effect on the total inventory (Lenzen, 2000). The inventory data can be measured and/or collected from the actual production sites within the system boundaries (primary data), or can be obtained or calculated from other sources such as LCI databases (secondary data).

The unavoidable cut-offs are one of the major drawbacks of PA based approaches, leading to truncation errors and thus to an underestimation of the environmental impacts that can reach up to 50% (Lenzen, 2000; Williams et al., 2009). Moreover, PA usually requires large amounts of data and thus it implies high effort and time investments. This method, however, allows achieving very detailed results when applied to particular products or processes, since each environmental burden is linked to a specific step of the life cycle.

After two decades (1970-1990) where the first life cycle based environmental assessments were carried out, characterised by diverging approaches, terminologies, and results, the Society of Environmental Toxicology and Chemistry (SETAC) contributed decisively to the standardization and widespread of the Life Cycle Assessment methodology, by means of a series of meetings and workshops which lead to the development of guidance documents, such as the SETAC code of practice, that ultimately served as basis to the first ISO standard on LCA in 1997 (Fava et al., 2014). Thus, the 1990s are considered the decade of standardization, when LCA was incorporated into policy (especially in packaging regulations), and when some of the first broadly accepted impact assessment methods were developed (Consoli et al., 1993; Guinee et al., 2010).

The pioneer LCA studies carried out within the aforementioned framework applied the process analysis approach (Guinée et al., 1993). PA is in fact often referred to as conventional LCA (Lenzen, 2000; Matthews and Small, 2000). Many of these pioneer studies evaluated packaging materials (Hocking, 1991; Mekel et al., 1990), but the application subjects were broadened throughout the decade of 1990 (Andersson et al., 1994; Furuholt, 1995).

In the 2000s, the conventional LCA methodology experienced a rapid development, due to the creation of national LCA networks, the updating of the ISO standards, and the broad incorporation of LCA into policy (Guinee et al., 2010). The decade was also characterised by a new methodological diversification, which implied (among others) a substantial development of IO and hybrid approaches for inventory compilation (Guinee et al., 2010).

Among the most recent challenges of the LCA methodologies, uncertainty analysis, regionalization of the impact assessment methods and the incorporation of the social and economic dimensions of sustainability have been identified (Hellweg and Milà i Canals, 2014).

PA is considered the most common approach for inventory compilation in LCA studies (Chastas et al., 2016; Suh and Huppes, 2005). This approach is most frequently used for the assessment of products (Colangelo et al. (2018); Guerrero and Muñoz (2018); Noya et al. (2018)) and processes (Aguilar-Sánchez et al. (2018); De Marco et al. (2018); Khoshnevisan et al. (2018)), even though a few larger scale applications exist. Some examples of the latter are the LCA of consumption in Belgium (Jansen and Thollier, 2006) and Switzerland (Girod and De Haan, 2010); or that of the Galician fishing sector (Iribarren et al., 2010b, 2011b) or the Cornwall healthcare service (Pollard et al., 2013).

Input-Output (IO)

The input-output (IO) model developed by Leontief (1951) assumes that, within a certain economy, each sector consumes outputs of various other ones in fixed ratios, in order to produce its own output. Under this assumption, an intermediate demand matrix is defined such that each column shows the intermediate output (in monetary terms) of the various sectors required by a certain one to produce one unit of their output (Suh, 2004). The central equation of this method is the following Eq.1.

$$x=Ax+y \qquad \text{Eq.1}$$

where x is the total industry output vector, y is a vector of final demand and A is the aforementioned intermediate demand matrix, defined such that each column of A shows the intermediate industry input that is required to produce one unit of output. Thus, the total industry output x is equal to the industry output consumed by intermediate industries plus the industry output consumed by final consumers (i.e. households). Equation 1 can be transformed into Eq.2

$$x=(I-A)^{-1}y \qquad \text{Eq.2}$$

Following Eq. 2, the total industrial output (x) required to satisfy a certain final demand y can be easily calculated.

This IO framework can be extended with environmental data (Leontief, 1970), thus obtaining an Environmentally extended input-output model (EIO), which can be used for the calculation of environmental impacts. To do so, a matrix of environmental interventions B is added to the model (Eq. 3), assuming that the amount of environmental flows generated by an industry is proportional to its output. Thus, B is the matrix of environmental flows (emissions and resource consumption) linked to the production of one unit monetary output of each industry (Suh and Huppes, 2005).

$$C=Bx=B\cdot(I-A)^{-1}y \qquad \text{Eq.3}$$

Following Eq. 3, the matrix of total direct and indirect environmental flows linked to the satisfaction of a certain amount y is obtained, denoted here as C.

IO models can be Single Region Input Output matrixes (SRIO) and Multi Region Input Output matrixes (MRIO), which are briefly described below:

- SRIO matrixes: These tables are more simple and easy to obtain, and thus more frequently available. They contain data from only one country or region, whose imports are not specified by place of origin. Thus, the columns of the technology matrix A represent the inputs (both domestic and imported together) that are required to produce one unit of output. Thus, when SRIO matrixes are used for environmental assessment, it is assumed that any imported goods consumed in that region are obtained with the same technology and environmental interventions existing there, i.e. the Domestic Technology Assumption (DTA) (Wiedmann, 2009b). This simplification eases calculations but results in inaccuracies (Andrew et al., 2009). SRIO matrixes are available for Galicia (IGE, 2017d), Spain (INE, 2014), and numerous European and Worldwide countries (ABS, 2017; Eurostat, 2018; INSEE, 2013). These regional matrixes need to be combined with environmental data to create an EIO model that can be used for environmental assessment.
- MRIO matrixes: These matrixes contain data of several countries and regions, thus linking their imports and exports. Multi-regional EIO matrixes also include the environmental data of each region. When using MRIO tables, the A matrix is constituted of numerous submatrixes that represent the interactions between different countries, the final demand vector y provides information about the demand from each sector of each country, and the matrix of environmental flows is specific for each sector in each country. Thus, these tables are much larger than SRIO ones, and their availability, update and level of detail is usually lower. Some examples of these matrixes

containing environmental data are the World Input Output Database (WIOD, 2013), the GTAP database (GTAP, 2017), or Exiobase (Wood et al., 2015).

Broadly speaking, EIO approaches are suitable for large scale systems such as countries, but their applicability to particular products and processes is limited (Wiedmann, 2009a), since the assumption of fixed coefficients to define inter-sector flows and their link to environmental interventions is usually far from reality at the smaller scales. Moreover, their high level of aggregation (several heterogeneous products or processes are combined into single categories (Suh et al., 2004)), does not allow specifying which particular product or process is responsible for a certain burden. Last, IO methods can only provide pre-consumer LCI data (i.e. the use and downstream steps of a product cannot be modelled using IO), and their level of update is usually lower than that of PA data, since compiling IO tables is a very time consuming process (Suh and Huppes, 2005). However, once the IO tables are available, the time and data requirements are usually much lower than those of PA (Wiedmann and Minx, 2008).

From Leontief's first definition of an EIO model in 1970, several so called "environmental input output analyses" were carried out. Some examples of these first applications can be found in (Lenzen, 2000). The EIO approach however, was not integrated into LCA studies up to the early 1990s (Suh and Huppes, 2005). It is agreed (Wiedmann, 2009a) that the first application of EIO within the LCA framework was carried out by Moriguchi et al. (1993), who conducted the LCA of an automobile by combining PA (used for the main processes) with EIO data (for upstream flows). That study was in fact the first tiered hybrid analysis (see next subsection), since it combined both IO and PA methodologies.

The first EIO-LCA database[1] was created at the Carnegie Mellon University in the mid-1990s (Simonen, 2014): Lave (1995) was the first to propose using input-output analysis techniques in LCA studies to overcome the limitations of the PA approach, and combined the US

[1] http://www.eiolca.net/

IO tables with data from the US Toxics Release Inventory, to evaluate how certain increases in the final demand of products could affect both direct and indirect toxic emissions into the environment. Hendrickson et al. (1998) completed the existing model by including hazardous waste emissions, and they made their EIO-LCA tables available. Later on, Joshi (1999) significantly increased the number of environmental flows covered (global warming, acidification, and eutrophication, among others) and proposed several ways of using IO based data in the life cycle assessment of products.

The availability of pioneer EIO-LCA databases generalised the use of this approach in the late 1990s and the first 2000s (Suh and Kagawa, 2005). A milestone was reached at the end of the 2000s with the compilation of the first MRIO databases (Wiedmann et al., 2011).

Guinee et al. (2010) pointed at several needs for the future development of the LCA methodology in the present decade (2010-2020). The broadening from product-based analyses to economy-based ones was included among them, and the EIO-LCA approach was mentioned as an appropriate tool to do so. Thus, in the last decade, EIO approaches have been widespread in LCA studies, as summarized in a recent paper by Onat et al. (2017).

While PA approaches are used for the assessment of products and processes, IO based studies focus on large scale systems, and thus the approach is used to evaluate the impacts of sectors, whole supply chains and regional/national consumption activities (Minx et al., 2009).

Hybrid approaches

To overcome the aforementioned drawbacks of both PA and IO approaches, hybrid methodologies are frequently used, looking to benefit from the high level of detail of PA and the calculation simplicity and exhaustiveness of EIO tables (Wiedmann and Minx, 2008; Wright et al., 2011). Since hybrid methodologies benefit from both the advantages of PA and IO approaches, their use is deemed appropriate at any scale: from individual products to regional/national studies. Moreover, it is frequently argued that hybrid approaches provide more representative results than PA or IO methodologies alone (Majeau-Bettez et al., 2011). Hybrid approaches should however be used with care, since Yang et al. (2017) recently proved that using highly aggregated IO models can lead to higher errors than those caused by PA truncation, even though they were recently accused (Pomponi and Lenzen, 2018) of choosing an extreme example in their study (where PA had an unusually low truncation error and IO an unusually high aggregation error).

Several types of hybrid approaches exist (Crawford et al., 2018; Suh and Huppes, 2005):

- Tiered hybrid analysis: This approach uses IO based data to provide information that cannot be achieved by means of PA, but falls within the PA framework. Two possible procedures exist: in the first one, PA is applied for the use and downstream life cycle phases and also for the most important upstream ones, while the remaining upstream inventories are taken from IO databases; in the second approach, a PA based study is complemented with IO data, to account for inputs or outputs for which PA data are not available.
- Path Exchange Method: Within this procedure, an IO matrix is mathematically disaggregated into structural paths (supply chains), and the specific paths for which detailed data are available are replaced by PA-based information (Lenzen and Crawford, 2009).
- Matrix augmentation: It implies the disaggregation of the sector of the IO matrix to which the product under study belongs, in a way that the matrix can be completed with actual primary data (PA based) from the supply chain under study.
- Integrated hybrid analysis: The IO table is used to solve upstream and down-stream cut-offs where better data are not available. To do so, the PA inventories expressed in physical values are represented in a matrix which is then incorporated into the IO model, representing the remaining sectors of the economy (Suh et al., 2004).

As already mentioned, the tiered hybrid analysis carried out by Moriguchi et al. (1993) was the first attempt to integrate IO approaches into the LCA framework. Tiered hybrid analysis is the simplest hybrid approach, since it can be performed using commercial LCA software integrating both LCI and PA inventories (Strømman et al., 2009), and it does not require deeper knowledge of the IO framework. Thus, this type of analysis, in which PA based results are improved by just adding IO data to account for missing stages of the life cycle, is the most widely used hybrid procedure (Crawford et al., 2018). However, two major disadvantages characterise this approach: the system boundary definition, i.e. the choice of which processes are modelled with either IO or PA (which may imply truncation errors due to process omission); and double counting (Crawford et al., 2018).

Double counting[2] is a frequent issue when the life cycle inventories of products are combined to calculate larger-scale impacts (Lenzen, 2008), which affects both PA and tiered hybrid approaches. In the particular case of tiered hybrid LCA, double counting occurs when the same products and processes are considered both in PA and IO databases. Strømman et al. (2009) proposed an algorithm to systematically avoid double counting in tiered hybrid LCA approaches, although acknowledging that its complexity may be a barrier for its application. Moreover, Lenzen (2009) questioned Strømman's strategy for double counting identification, and the conditions set for its avoidance.

In practice, the double counting issue found in tiered hybrid LCA studies is usually resolved in each of them in an *ad hoc* manner (Crawford et al., 2018; Dias et al., 2017).

1.1.3 Life Cycle Impact Assessment

The third step of LCA consists of several mandatory stages and some optional ones (Figure 3).

[2] The double counting issue occurring when combining PA or hybrid LCIs to obtain large scale inventories will be referred to as *intra* double counting. This definition is meant to establish a difference with another type of double counting issue, mentioned in section 1.2.2.

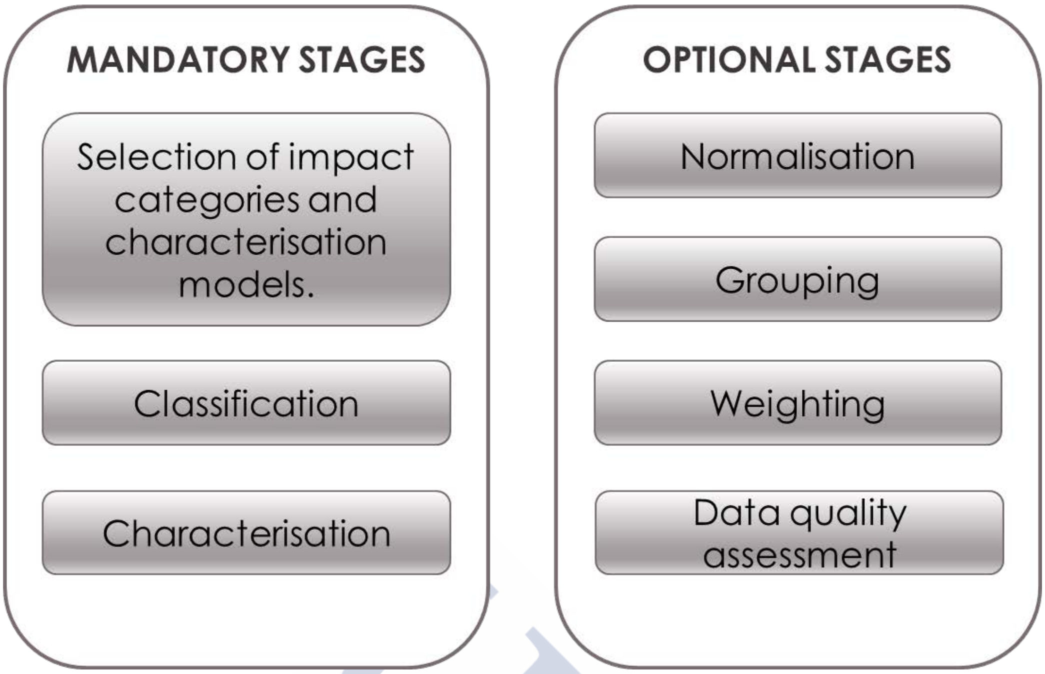

Figure 3: Stages of the Life Cycle Impact Assessment phase. Adapted from ISO (14040:2006)

The following two subsections focus, respectively, on the mandatory and the optional stages of the Life Cycle Impact Assessment phase.

1.1.4 Mandatory stages

As seen in Figure 3, three stages are required at the LCIA phase, which are further detailed below.

Selection of impact categories

The environmental interventions gathered in the previous phase and linked to each life cycle stage are associated with environmental impact categories at this point. These impact categories reflect the environmental impacts of the pollutants released and resources consumed in the inventories.

Impact categories can be chosen either at the midpoint or endpoint level, depending on at which point of the environmental mechanism of the stressor is evaluated:

— Midpoint categories. Midpoint indicators reflect some point on the environmental cause-effect chain between the substance emission or resource consumption and the damages, which are represented by the endpoint impacts. Some examples of midpoint categories are climate change, ozone depletion, eutrophication, acidification, etc.

— Endpoint categories. These indicators translate the midpoint impacts into damages: either to human health, natural environment, or natural resources.

The selection of impact categories and indicators must be linked to the goal and scope of the study, since they should provide a comprehensive set of environmental aspects that are relevant to the studied product or process.

Classification

At this stage, the resource stressors from the inventory are assigned to the impact categories selected, according to the substances' ability to contribute to different environmental problems. It should be noted that a single substance can contribute to different environmental impacts (ISO, 14044:2006).

Characterisation

In the characterisation step, the inventory flows are converted into impacts by means of several multiplicators, named characterisation factors, which convert the specific pollutant into the corresponding units of the impact category.

Several characterisation models exist both at the midpoint and endpoint level. The most widely used nowadays is probably ReCiPe 2008 model (Goedkoop et al., 2009), and so it has been chosen to determine the midpoint normalisation factors in this thesis. The Joint Research Centre of the European Commission created the International Reference Life Cycle Data System (ILCD), to develop guidelines that complement available LCA standards. Within the ILCD framework, a study was carried out comparing LCIA methods at the midpoint and endpoint level, identifying the best option among the different characterisation models available, and classifying them according to their reliability (Hauschild et al., 2013). The ILCD recommendations are coincident with the ReCiPe 2008 model in numerous midpoint impact categories (Owsianiak et al., 2014).

The following midpoint impact categories from ReCiPe 2008 have been used in this document to obtain the Galician set of normalisation factors, and thus they are briefly defined below:

- Climate change: Equivalent to the carbon footprint, this midpoint impact category reflects the amount of greenhouse gases (GHG) emitted to the atmosphere and contributing to climate change, expressed as CO_2. Due to the high diffusion of the climate change/carbon footprint indicator, and to its relevance in this thesis, more attention will be paid to this impact category later on in this section.
- Ozone depletion: Refers to the destruction of the ozone layer, caused by anthropogenic emissions of Ozone Depleting Substances (ODS). This midpoint impact expresses all ODS emissions in a single unit, CFC[3]-11.
- Terrestrial acidification: Expressed in units of SO_2, this impact refers to the atmospheric emissions of acidifying substances, which are subsequently deposited on the soils and contribute to pH decrease.
- Freshwater eutrophication: Increase of nutrients in freshwater due to anthropogenic activities (e.g. fertilization), which leads to the overgrowth of plants and algae. This midpoint impact category expresses all nutrient emissions to freshwater in units of P, the limiting nutrient (whose scarcity limits biomass growth).
- Marine eutrophication: Similar to the previous one, it refers to marine waters and it is expressed in units of N, the limiting nutrient for seawater.
- Human toxicity: Midpoint impact category referring to the emissions of toxic substances that can negatively affect human health. It is expressed in units of 1,4-DCB[4] emitted to air.
- Photochemical oxidant formation: This midpoint impact is linked to the human health damage caused by ozone exposure. Ozone is not directly emitted into the atmosphere, and so this

[3] Chlorofluorocarbon
[4] Dichlorobenzene

impact is expressed in units of NMVOC[5] (a precursor to ozone) emitted to air.

- Particulate matter formation: Similarly to the previous one, this impact is linked to the human health damage caused the emissions of particulates to air, and it is expressed in units of PM_{10}[6].
- Terrestrial ecotoxicity: Refers to the emissions of toxic substances to soil, and it is expressed in units of 1,4-DCB.
- Freshwater ecotoxicity: Refers to the emission of toxics to freshwater, expressed in units of 1,4-DCB.
- Marine ecotoxicity: Similar to the previous ones, refers to the emissions of toxic substances to seawater, expressed in units of 1,4-DCB.
- Ionising radiation: Linked to the damage caused to human health by the release of radioactive material to the environment, this midpoint indicator is expressed in units of Uranium-235 emitted to air.
- Agricultural land occupation: It refers to the occupation of land for agricultural uses, which damages existing ecosystems. It is expressed in units of area·time (e.g. m^2·year), referring to the amount of land occupied during a certain period of time.
- Urban land occupation: Similar to the previous one, refers to the occupation of land for urban uses, and it is also expressed in units of area·time
- Natural land transformation: This impact category refers to the land use transformation leading to agricultural or urban occupation. It is expressed in units of area.
- Water depletion: This midpoint indicator reflects water consumption in volumetric units (usually m^3). In practice, no characterisation models are used for this indicator in ReCiPe, and thus, according to the applicable ISO for water footprint (ISO, 14046:2014), this indicator corresponds to a water footprint inventory analysis. Due to the use of both the water

[5] Non-Methane Volatile Organic Compounds
[6] Particulate Matter with a diameter of less than 10 µm.

depletion and the water footprint in this thesis, further attention will be paid to both indicators later on.

- Metal depletion: It refers to the consumption of metal and mineral resources, and it is expressed in units of Fe extracted.
- Fossil depletion: Similar to the previous one, this indicator refers to the consumption of fossil resources, expressed in units of oil equivalents.

All midpoint indicators in ReCiPe can be calculated following 3 different perspectives, which refer to different modelling choices:

- Individualist (I): Based on the short-term interest, this is the most optimistic approach, considering a certain adaptation capacity to the impacts due to future technology developments.
- Hierarchist (H): This intermediate perspective is based on the most usual policy time-frames, it is a consensus model usually considered as the default one.
- Egalitarian (E): Based on the longest term perspective, it is the most precautionary approach, and it does not consider technology adaptations to the environmental impacts.

It should be noted that an updated version of the ReCiPe model (Huijbregts et al., 2017) was made available during the final stages of this thesis. It was discarded to use this new version for the compilation of the Galician NFs, since no normalisation factors obtained with the new methodology are available so far, and a comparison of the Galician references to the existing ones to identify similarities and inconsistencies was deemed necessary. However, and once all the Galician LCI data are available, the calculation of the NFs with the new methodology is straightforward.

Two midpoint indicators have been mainly used in the various articles that compose this thesis, the carbon and the water footprint. Thus, further attention is paid to both of them below.

<u>Carbon footprint</u>

Equivalent to the ReCiPe Climate Change midpoint impact, the Carbon Footprint (CF) is the most widely used LCA-based indicator (Weidema et al., 2008). This midpoint indicator expresses the amount of GHG emitted to the atmosphere throughout the entire life cycle of a product, process or service, which are converted to CO_2 equivalents by considering their different radiative forcing (i.e. a measure of how the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere is influenced when actors that affect climate –such as GHG concentrations- are altered (IPCC, 2007)).

Being easily understood by non-experts, this indicator has been frequently used in product labelling (AENOR, 2013; Levante-emv, 2017; TESCO, 2012), and a specific standard (ISO, 14067:2013) and certification schemes exist to that end (AENOR, 2015; Carbon Trust, 2012). CF has thus been widely applied to products (Chiriacò et al. (2017); Ibidhi et al. (2017); Vinyes et al. (2018)), but also to services (Duane et al., 2017; Malik et al., 2018; Puig et al., 2017) and entire regions (Brizga et al., 2017; Kanemoto et al., 2016).

It should be noted that the CF, despite being the most widely used indicator of environmental sustainability, is not a good representative of all the environmental burden of a certain product or process. Thus calculating (and tackling) this issue alone can shift the impacts to other spheres of the environment (Laurent et al., 2012).

<u>Water footprint</u>

According to the applicable standard (ISO, 14046:2014), a water footprint assessment is defined as the *"compilation and evaluation of the inputs, outputs and the potential environmental impacts related to water used or affected by a product, process or organization"*. The standard stablishes a difference between water footprint inventory reporting, where the volume of freshwater consumed is calculated and reported, but no characterisation methods are used, and water footprint impact assessment reporting, which complements the former by means of a characterisation model that takes into account water scarcity (i.e. consuming 1 m^3 of water from a scarce region does not have the same impact as doing it from a water-abundant one).

The most widespread scheme for water footprint inventory reporting is that of the Water Footprint Network (Hoekstra et al., 2011). This methodology considers three components that make up water footprint:

- Blue water: Freshwater (surface and groundwater) withdrawn from aquifers and then consumed, i.e. evaporated or incorporated into the product. This component is equivalent to the ReCiPe water depletion midpoint impact mentioned above.
- Green water: Rainwater stored as soil moisture that is consumed by crops and trees.
- Grey water: Amount of freshwater required for diluting a certain amount of pollutants which are released into freshwater. Unlike the previous two, this component does not account for water consumption, but it is expressed in units of water as a strategy to account for water pollution in the same units as the previous ones. This grey component is controversial (Ridoutt and Pfister, 2013) and, by definition, it does not comply with the LCA framework, and thus it is frequently left out in LCA studies including water footprint (Jefferies et al., 2012; Page et al., 2012).

Regarding the water footprint impact assessment reporting, a consensual midpoint characterisation model for freshwater consumption (i.e. blue water) has been recently achieved (Boulay et al., 2018). This scarcity based characterisation model allows considering the potential to deprive another freshwater user (human or ecosystem) by consuming freshwater in a certain region (Boulay et al., 2015).

The green water component is also considered in LCA based studies but, unlike in the WFN approach (Quinteiro et al., 2018), the net green water concept is used (Núñez et al., 2013; Quinteiro et al., 2015), defined as the difference between the green water flow of the crops or forests assessed and that of a reference, natural land use. No consensual characterisation model for green water exists so far, even though some proposals are available to take into account green water scarcity (Núñez et al., 2013; Quinteiro et al., 2015).

1.1.5 Optional stages

Once all the mandatory stages of the LCIA phase have been carried out, ISO (14044:2006) contemplates further optional ones, which can help fulfilling the goal and scope of the analysis.

Normalisation

Normalisation compares the LCIA results to a reference (e.g. the total impacts per capita per year). This step is carried out following Eq. 4.

$$N_i = C_i / NF_i \qquad \text{Eq.4}$$

Where Ni is the normalised result of the impact category i, Ci is the characterised impact of the product or process under study and NFi is the normalisation factor, i.e. the reference against which the results are compared. The reference system chosen (temporal and geographical) should be consistent with the LCIA goal and scope, and it is recommended to use several reference systems to ensure the robustness of this step.

There are two main types of normalisation (Pizzol et al., 2016):

- Internal normalisation is used to compare the environmental performance of different alternative scenarios within the same study. It can be carried out in several ways (Laurent and Hauschild, 2015; Norris, 2001):
    - Division by baseline (DBB), in which the impacts of each alternative are divided by those of a certain one, which represents the baseline scenario (e.g. Boughton and Horvath (2006)).
    - Division by maximum (DBM), in which the impacts of each category are divided by the maximum value found for that category throughout all the alternatives considered (e.g. Chevalier et al. (2003)).
    - Division by sum (DBS), in which the impacts of each category are divided by the sum of the impacts for all the studied alternatives within that impact category (e.g. Dryden (2006)).
- External normalisation refers to the impacts of a certain reference system, usually a geographical area (which maybe global, regional, national, or local) at a specific period of time

(usually one year) (Lautier et al., 2010). There are two main types of external normalisation:

- The consumption based approach, in which the impacts generated by the consumption activities of the area are chosen as NFs.
- The production based approach, whose NFs are the direct impacts of all the activities taking place within the area (Breedveld et al. 1999).

Internal normalisation has been progressively abandoned (Laurent and Hauschild, 2015) due to the development of external normalisation, which can serve the same purposes without suffering from the downsides of the internal approach (i.e. it can only be used in comparative scenarios, different approaches (DBB, DBM, DBS) can lead to different conclusions if a subsequent weighting step is carried out and the conclusions are insensitive to the magnitude of the impacts (Norris, 2001)). Thus, the current recommendation of the UNEP-SETAC is to use external normalisation instead (Verones et al. 2017).

Within the external approaches, either the consumption based normalisation references or those obtained for the whole world are preferred (Lautier et al., 2010), since in the current global economy, where numerous products consumed in a certain region come from different ones, the country-based or region-based production NFs are often not representative of the actual worldwide productive conditions.

Numerous authors have published their external normalisation datasets, most of them following the production approach. The most relevant ones are summarised in Table 1.

Table 1: Literature review of existing external normalisation datasets

Study	Region(s) covered	Approach	Data year	Characterisation methodologies
Breedveld et al. (1999)	The Netherlands	Consumption	1993/1994	CML
		Production	1993/1994	
	West Europe	Production	1990/1994	
Huijbregts et al. (2003)	The Netherlands	Production	1997/1998	CML
	Western Europe	Production	1995	
	World	Production	1990	
			1995	
Bare et al. (2006)	United States	Production	1999	TRACI
Sleeswijk et al. (2008)	Europe	Production	2000	ReCiPe
	World	Production	2000	
Lautier et al. (2010)	Canada	Production	2005	IMPACT 2002+, TRACI, LUCAS
	United States	Production	2008	
	North America	Production	2005/2008	
Laurent et al. (2011)	Europe	Production	2004	EDIP97, EDIP2003
Dahlbo et al. (2013)	Finland	Consumption	2005	ReCiPe
		Production	2005	
Kim et al. (2013)	United States	Production	2006	TRACI
Slapnik (2015)	Slovenia	Production	2007–2012	ReCiPe
Sala et al. (2015)	Europe	Production	2010	ILCD

Normalising allows identifying inconsistencies in the LCIA results, provides a context and gives information about the relative importance of the various impact categories, and serves as a first step for the following optional stages. Some recent examples of the application of the normalisation step in case studies are those of Abín et al. (2018), who used normalisation to identify to which impact categories the egg production of a Spanish farm contributed the most; and Corbala-Robles et al. (2018), who used normalisation and weighting to identify the most environmentally friendly manure handling scenario (treatment versus direct land application).

Although optional, this step is increasingly being used in the literature (Figure 4, a), and for years the number of LCA papers including this step has been relatively stable (2% of the total LCA studies, on average, Figure 4, b)

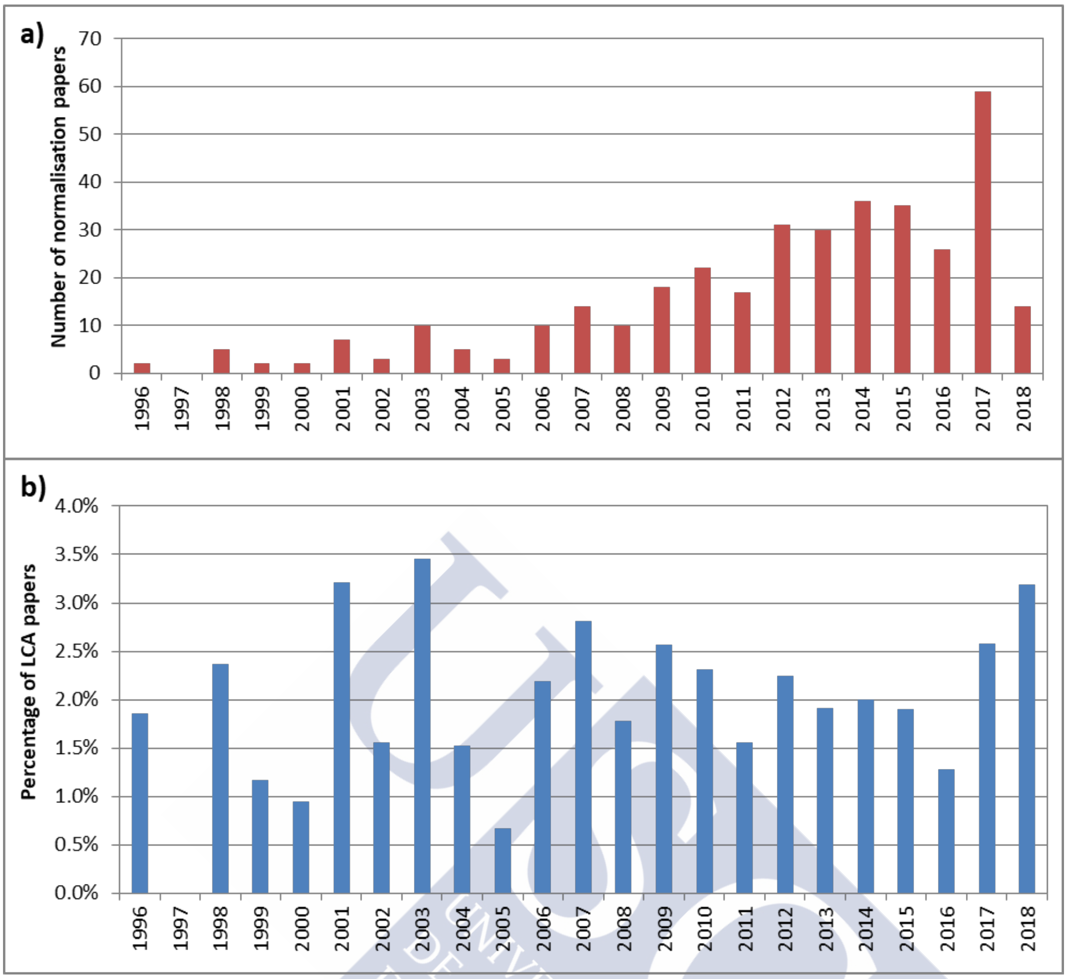

Figure 4: Evolution of the number of LCA scientific papers including normalisation. a) Number of papers. b) Percentage of the total LCA studies. Source: Scopus. Date of retrieval: February 2018.

The fact that the ILCD recently published European normalisation factors (Sala et al., 2015) proves the existing interest of the LCA community into this optional step. Moreover, a recent study (Pizzol et al., 2016) surveyed LCA experts about normalisation, and found out that it was perceived as relevant for decision making, and that it was correlated with the perceived robustness, transparency, relevance and validity of the studies, but poorly correlated with uncertainty.

Grouping

It consists of aggregating impact categories into several groups. Each group can either share certain common characteristics (e.g. refer to the extraction of resources), to a certain degree of urgency (e.g. crucial environmental concerns (Graedev, 1997)), or to a certain impact scale (e.g. global, regional and local (Yi et al., 2011)). This is probably the least common optional step in LCIA, as proven by its exclusion from the ILCD guidance document for Life Cycle Assessments (ILCD Handbook, 2010), due to its alleged lack of usefulness for decision making.

Weighting

This optional step allows expressing all normalised LCIA results into equivalent units, and it may involve summing all the results into a single indicator. To do so, impact categories are weighted based on value judgements. Due to the high subjectivity of this step, LCIA results before weighting should always be made available along with the weighted ones (ISO, 14044:2006).

Data quality assessment

This step refers to any further analysis on data quality, being gravity, uncertainty and sensitivity analysis the specific procedures defined in ISO (14044:2006). A gravity analysis identifies the data which contribute mostly to each impact category result; an uncertainty analysis determines how assumptions and uncertainties in data affect the reliability of the results; and a sensitivity analysis indicates how changes in data and methodological choices affect the outcome of the study.

1.1.6 Interpretation

The last phase of an LCA involves analysing the findings of the previous ones together, in order to identify the significant environmental issues, but also to evaluate the robustness of the results, and to reach conclusions, explain limitations and provide recommendations.

The conclusions and recommendations obtained in this stage are linked to the goal and scope of the study. If the study is aimed at improving the environmental performance of a certain product, recommendations on which hotspots to tackle can be obtained from this stage.

Once the interpretation step is concluded, the results obtained can be used to provide information to decision makers (for priority setting, or product redesign), but also to consumers, through ecolabels.

1.2. Territorial LCA

The Life Cycle Assessment methodology can be applied to calculate the environmental impacts linked to the activities occurring in a certain territory. One of the procedures to do so is the territorial LCA approach, developed in 2013 by Eléonore Loiseau, which is the methodological core of this document. However, before that LCA framework was created, several authors had already assessed the environmental impacts of territories. In the last few years, measures to improve Loiseau's approach have also been proposed. Thus, this section is split into three subsections: the first one describes the pioneer LCA studies of territories, the second one focuses on the territorial LCA approach, and the third one presents the latest developments of that methodology.

1.2.1 Pioneer Life Cycle Assessments of territories

Seppälä et al. (2005) carried out an eco-efficiency assessment of a region in Finland, by evaluating economic and environmental (LCA based) indicators, which were then combined into eco-efficiency ratios (value of products and services divided by their environmental impacts). The authors followed two different approaches to assess the eco-efficiency of the production activities in the region: either considering only the activities (and their environmental impacts) occurring within the region; or also considering the upstream activities (and impacts) linked to them (i.e. the imports). The latter represents a cradle-to-gate life cycle assessment of the production activities of the territory.

Azapagic et al. (2007) proposed a mathematical framework for integrating LCA and Substance Flow Analysis (SFA) in the environmental assessment of urban areas. The authors distinguish between a foreground system (including all the activities taking place within the area) and a background system (including the external activities required to supply the necessary inputs in the area and to manage the waste leaving it). These definitions are consistent with those of direct and indirect impacts, respectively. SFA is thus used to track the pollutants in the foreground system, coupled with LCA to quantify the emissions of pollutants and their impacts both in the foreground and background systems. The procedure was illustrated by means of a theoretical case study, and only a few urban activities were accounted for (e.g. car transport, waste management). Azapagic et al. (2013) start from their aforementioned LCA/SFA integration and propose an integrated decision-support framework (and software), to enable more sustainable management of urban pollution. They test their framework in a real UK case study. In practice, however, only a few activities (steel manufacturing, wastewater treatment, and transport) are considered again. It should be noted that Azapagic and colleagues provide the impact results of both their studies split into foreground and background systems.

Goldstein et al. (2013) proposed coupling the Urban Metabolism (UM) approach with LCA, into a model to calculate the environmental impacts at the city level. The UM approach accounts for the metabolic demands of the cities under study, considered as the inventory flows of the use stage of a conventional LCA study, which are then completed with the upstream (extraction and pre-processing of the flows used) and downstream (end of life of the waste generated) processes linked to the use phase by means of PA based LCA. The metabolic flows included in the assessment were food for residents, water for all uses, fuels for transport, electricity and several materials consumed within the cities (metals, plastic, cardboard etc.). The authors apply the procedure to five cities for which UM studies are available, and conclude that the methodology could be improved by incorporating a hybrid approach for inventory compilation instead of PA only.

A more frequent approach in the literature is to use IO based or hybrid LCA approaches to obtain the environmental impacts linked to the consumption activities of a region or country. Numerous examples of the calculation of the impacts of this territorial consumption can be found in the literature, determined at different scales such as countries (e.g. (Barrett et al. (2013); Brizga et al. (2017)), and at the region (Ivanova et al., 2017; Zhou and Imura, 2011) and city level (Dias et al., 2014; Heinonen and Junnila, 2011; Vause et al., 2013).

LCA has also been used as a tool for strategic planning: several authors have combined the EU Strategic Environmental Assessment[7]

[7] The protocol on SEA applies to certain types of public plans and programmes (e.g. on agriculture, transport or energy), which should include an environmental assessment at the earliest stages, in which the significant

(SEA (European Comission, 2001)) with LCA to foresee the environmental impacts of plans and programmes: Finnan et al. (2012) calculated the environmental impacts of an Irish government plan to replace 30% of peat consumed in power plants by biomass; Björklund (2012) used LCA to evaluate local energy planning, comparing the environmental performance of the various alternative energy systems included in the SEA; Bidstrup et al. (2015) proposed including LCA into SEA at an even earlier stage, to help designing plans and programmes, and tested the procedure in Danish extraction planning.

1.2.2 The territorial LCA approach

Loiseau et al. (2012) evaluated the existing tools for the environmental assessment of territories required by the SEA directive: LCA, environmental risk assessment, ecological footprint, material and energy flow analysis, exergy and emergy. The authors compared the approaches based on five criteria (i.e. level of maturity, type of system modelling, inventoried flows, indicators provided and usability of the method), and it was concluded that LCA was the most promising method for the environmental assessment of territories, although it was acknowledged that several limitations still existed: the lack of site-specific characterisation factors (which account for the particular sensitivity of the territory under study), and the need for a consistent definition of the functional unit (being territory a multifunctional system). The authors also concluded that no study had so far calculated the impacts linked to all the human activities taking place within a certain territory (i.e. both consumption and production activities).

Starting from their previous conclusions, Loiseau et al. (2013) proposed an adapted LCA framework (i.e. **territorial LCA**) to conduct the SEAs required in land planning. When designing that approach, four major issues were identified, and solved as follows:

a) Functional unit definition, being the territory a multifunctional system: the territory with a specific land planning scenario was defined as the reference flow, and thus the functional unit was replaced by the functions linked

effects on the environment (and alternatives to the plan or programme) are identified.

to that reference flow (e.g. provision of jobs, provision of food, etc.).

b) Boundary selection, or how to allocate environmental responsibilities to the territories: the total responsibility approach (Eder and Narodoslawsky, 1999) was chosen, where the territory is responsible for all the impacts of both its final consumption and its production activities, even if this generates a double counting[8] at a global scale. To avoid this double counting within the territory, it was decided that consumption and production impacts should be reported separately.

c) Data collection, or how to obtain LCIs for all consumption and production activities: activity descriptors are used for both consumption and production. The expenditures of the inhabitants of the territory on a particular commodity, or the amount of electricity consumed at their households are examples of consumption activity descriptors, while the annual output of a certain product manufactured in the territory, or the annual mineral extraction there are examples of production descriptors. These descriptors are then combined to LCI databases, to link the functions to their inventory data, following a hybrid approach. If the activity descriptors are physical flows, a PA approach is used and PA databases such as Ecoinvent are used (Wernet et al., 2016), while if monetary flows are only available, EIO tables such as the USEIO database (Suh, 2010) are used.

d) Refining of impact assessment methods, or the need to distinguish direct and indirect impacts and to account for territorial sensitivities: as already done by Azapagic and colleagues, impacts are split into on-site and off-site, to distinguish the impacts which take place on the territory from those occurring elsewhere. Moreover, impact categories were split into global or regional/local impacts, which would

[8] This *inter* double counting is different to the already defined *intra* double counting (arising when combining PA or hybrid LCI data, see section 1.1.2). *Inter* double counting appears when summing the impacts of consumption and production activities of a certain territory.

allow using regionalized characterization factors to account for the particular characteristics of the territory at stake.

Thus, this new framework links the territory to its functions, providing two outputs: a vector of environmental impacts and also a vector of land use functions provided by the territory (i.e. goods and services). The methodology allows comparing different land planning alternatives, which by definition would provide different functions, in a quantitative way. Loiseau and colleagues use their framework in a case study of a hypothetical territory, for which they account for the provided functions (number of employees, number of tourists, GDP, etc.) and the linked environmental impacts (evaluated at the endpoint level with the ReCiPe methodology, and split into consumption and production, global and local, and direct and indirect).

Loiseau et al. (2014) then applied their territorial LCA framework to a French Mediterranean territory, whose activities were linked to their environmental impacts at the endpoint level. The case study was conceived as a baseline, required prior to defining and assessing land planning scenarios. Three types of territorial functions were considered: societal, economical or environmental, which were assessed through performance indicators (e.g. number of dwellings, GDP, surface of protected areas). To obtain the life cycle inventories of both production and consumption activities, a hybrid approach was followed again: PA based LCIs were used when available, and otherwise the USEIO database was chosen. The impacts of both types of activities were obtained using the ReCiPe endpoint characterisation, and they were split into consumption and production, and also between on-site and off-site impacts. Several weaknesses of the methodology were identified, mainly linked to the enormous amount of data required (and the data gaps found, which required assumptions), and to the use of the USEIO database in a European case study. A third weakness related to hybrid approaches was not identified at the time: the possible *intra* double counting among production activities, originated when an output of a certain industry is used as input for a different one within the same territory. This limitation, which was not a major issue for the French study due to the small size of the territory, would need to be addressed if the methodology were applied to larger, more self-sufficient regions.

1.2.3 Latest developments of the territorial LCA framework

Nitschelm et al. (2016) proposed to combine territorial LCA with spatialized LCA for the assessment of agricultural territories (in which most land uses or economic activities are based on agriculture) of 100-10,000 km^2. Since territorial LCA assesses the territory as a black box, whose activity impacts are the same no matter their specific location within the territory (i.e. the characterisation models are the same within the region), Nitschelm and colleagues incorporated spatialized LCA into territorial LCA, in a methodology (named spatialized territorial LCA or STLCA) aimed at obtaining more accurate results. STLCA proposes an extension of the LCA framework in which six steps are considered: (1) definition of the geographic boundaries and activities to be included; (2) definition and location of emission typologies (i.e. zones of similar environmental characteristics for emissions) and impact typologies (i.e. zones of similar sensitivity or characterisation factors); (3) determination of the spatialized life cycle inventories of each emission typology; (4) calculation of the environmental impacts by combining spatialized LCIs with the impact typologies; (5) mapping of the resulting impacts inside and outside the territory; (6) results interpretation using sensitivity and uncertainty analysis. This STLCA method is still under development, and it is so far meant for agricultural territories. Nitschelm et al. (2016) acknowledge that the method needs to be tested with real case studies to determine its applicability (in a previous study, Nitschelm et al. (2014) refer to an ongoing project in Brittany (France)), and that some methodological issues remain to be solved (linked to steps 4 and 5). Once the methodology has been fully developed, tested and proven useful, it would still need to be expanded to include human activities other than agricultural ones.

Mazzi et al. (2017) propose combining Environmental Management Systems (EMS) with territorial LCA, and evaluates its feasibility by means of a case study. EMS (e.g. the European EMAS[9]) are aimed at reducing the environmental impacts of organizations, through continuous improvement. The EMS certification system has been increasingly adopted by municipalities, where all of the territories

[9] Eco-Management and Audit Scheme

managed by the public administration act as the "organization" that adopts the EMS. Mazzi et al. (2017) combined the data contained in the EMAS Initial Environmental Review (IER) of an Italian municipality (i.e. water, fuel and electricity consumption and waste generation in public buildings) with that obtained for inhabitants and tourists visiting the region, and they used PA to obtain the life cycle inventories of the consumption activities of the municipality. Last, they compare the major environmental issues identified with LCA to those found by the EMS significance assessment, concluding that the combination of both approaches leads to a more comprehensive view of the territorial impacts. Mazzi et al. (2017) claim to overcome one of the main drawbacks of territorial LCA (i.e. data collection), by using the primary data already included in the EMS. However, they do not carry out a proper territorial LCA, since they do not account for the impacts of all consumption and production activities occurring within the municipality (i.e. they only account for a few inputs used within the municipality due to the lack of primary data).

Even though the territorial LCA methodology is at an early stage of development, the lack of formal terminology in existing studies led their authors to establish a classification to group future literature on the subject (Loiseau et al., 2018):

- Type A territorial LCA applications, which aim at assessing only one activity linked to the particular territory at stake. Studies considering the local conditions in one or several LCA stages already existed in the literature before territorial LCA was conceived (e.g. those using site specific characterization factors). Thus, Loiseau and colleagues simply propose to group these existing LCA practices under this nomenclature, and encourage practitioners to consider the territorial specificities throughout the four LCA phases.

- Type B territorial LCA refers to the methodology actually conceived by Loiseau and colleagues, to account for all the impacts of a certain territory (all production and consumption activities considered from a life cycle perspective). This approach provides an environmental baseline scenario for the territory that could be used to evaluate prospective spatial planning.

In their last publication, Loiseau et al. (2018) compare both territorial LCA approaches (through case studies) to conventional LCA, throughout the four LCA stages, and the main challenges faced by both methodologies are pointed out: i) the need for spatial differentiation at both the LCI and the LCIA stages (as also proposed by Nitschelm and colleagues); ii) the integration of the social dimension both at the goal and scope (e.g. definition of the territorial functions) and LCI stages (e.g. link of the emissions to socio-economic drivers); and iii) the use of consequential LCA when territorial LCA is meant for decision support and not merely impact accounting.

It should be noted that, by definition, type B territorial LCA can be used to calculate the impacts of all the consumption and production activities of a certain territory, following a life cycle perspective. Since these impacts would reflect the environmental baseline of the area, they could be used as normalisation factors for both consumption and production activities. The so-obtained regional NFs would reflect the particular characteristics of the area, but the use of the life cycle perspective would also avoid the issues related to the use of regional NFs instead of worldwide ones.

Chapter 2: Description of the case study: Galicia

This chapter describes the region in which this thesis focuses. A first section describes the general characteristics of the region, while the second one details existing LCA based studies in the area.

2.1. General characteristics

Galicia is one of the 17 territorial administrative entities (named Autonomous Communities) in which Spain is divided (BOE, 1978). The Autonomous Communities possess a certain degree of legislative autonomy, having particular executive and administrative powers and their own governing bodies.

2.1.1 Geography and climate

Galicia is located in the northwest of Spain, and it has a surface area of 29,574 square kilometres (IGE, 2017b). It is bordered by the Atlantic Ocean to the north and west, by the autonomous communities of Asturias and Castile-León to the east, and by Portugal to the south (Figure 5).

Figure 5: Location of Galicia.

The terrain of Galicia is hilly, and several mountain ranges (reaching up to 2.127 m) isolate the region from the rest of Spain and Portugal. Numerous rivers cross the region, discharging into another geographical particularity of the area, the Galician rías. These coastal inlets are characteristic of the Galician landscape, being much more scarce in the rest of the country, and they originated from fluvial valleys that were flooded by the rise of the sea level (Pagés-Valcarlos, 2000).

Following the Köppen-Geiger Classification System, the Galician climate is temperate with dry or temperate summer (Csb) (AEMET, 2011). However, very important climatic variabilities exist within the region, especially between coastal and interior, mountainous areas. Broadly speaking, the region has milder temperatures and higher annual precipitation values than the rest of Spain (Figure 6).

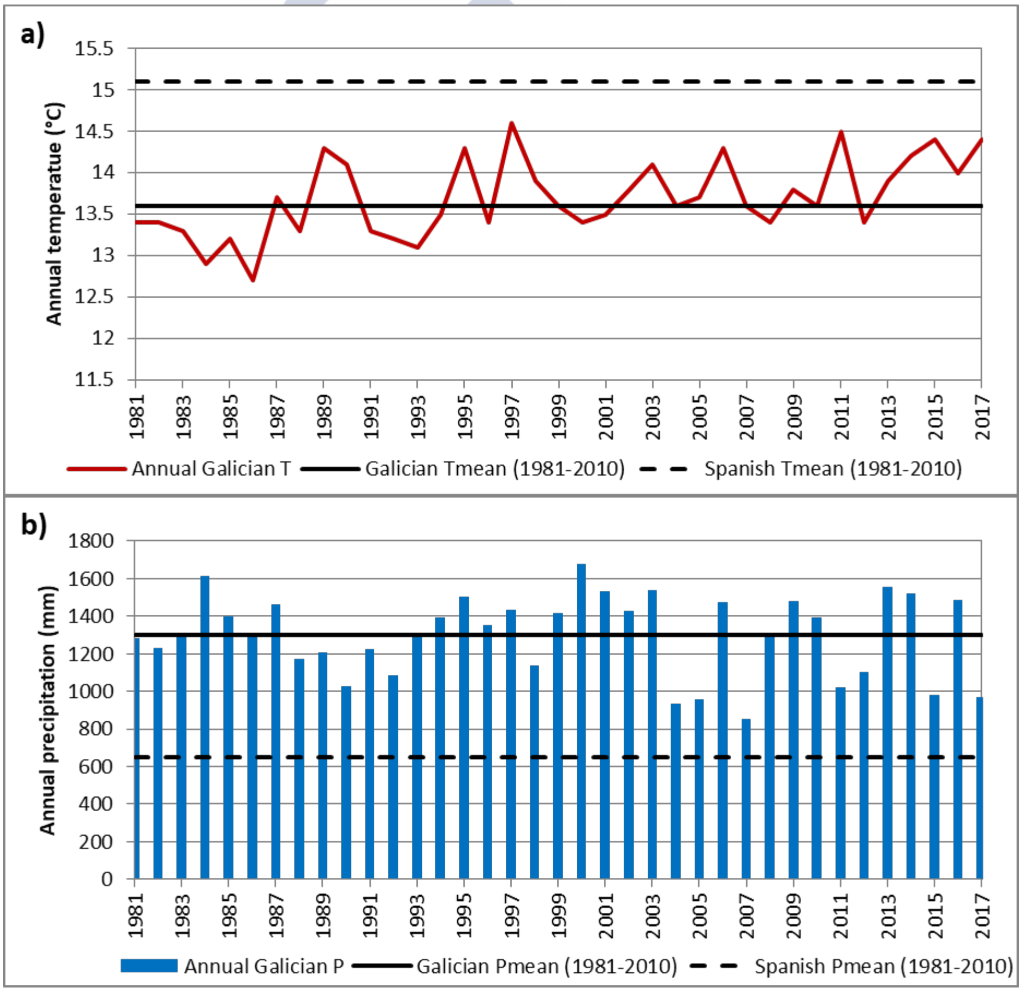

Figure 6: Evolution of the mean Galician annual climatic parameters, and comparison to long-term Galician and Spanish averages (MeteoGalicia, 2016). a) Temperatures. b) Accumulated precipitation.

2.1.2 Demography

According to the last census, Galicia has a population of 2.718.525 inhabitants (IGE, 2017b), less than 6% of the total population of Spain, and a population density of 92 inhabitants/km^2, matching the country average. However, Galicia has traditionally been a rural area, and thus its population is much more dispersed along the territory, living in numerous small villages. Most of the Galician inhabitants (65%) live in villages of less than 50,000 inhabitants. In the past few decades, there has been a tendency among the new generations of moving into the cities, while frequently older people stay in smaller villages: 70% of the inhabitants older than 60 live in rural areas while 63% of those younger than 30 live in the cities (IGE, 2017e).

The aging of the Galician population is a major issue within the community: even though the population of the area has risen along the last century, the trend has been reversed in the last few decades (Figure 7, a). In 2002, 33% of the population was under 30 years old, a figure which has decreased up to 25% in 2016 (Figure 7, b).

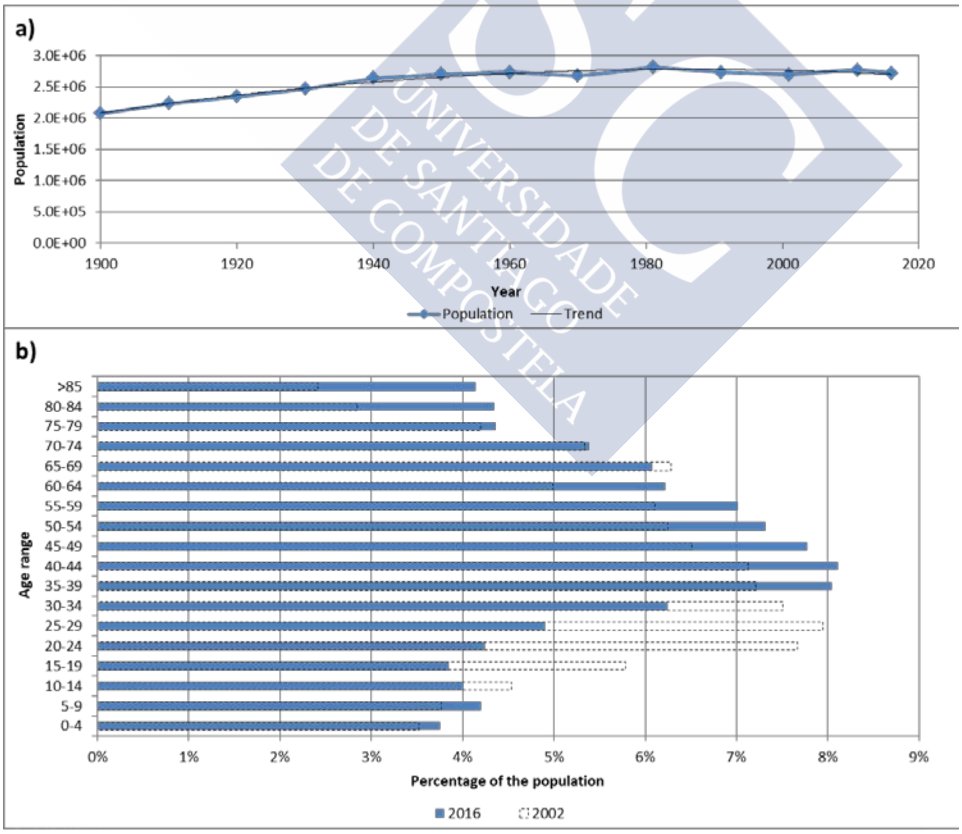

Figure 7: Galician demographics (IGE, 2017f). a) Evolution of the population (1900-2016) (IGE, 2017c). b) Evolution of the age of the population (2002-2016).

2.1.3 Government and policy

The Spanish Autonomous Communities are governed according to the Spanish constitution and their own organic laws, named Statutes of Autonomy, hierarchically located under the constitution but above any other law, and which contain the political competences that each community assumes.

The Galician Statute of Autonomy provides the region with certain political competences. Among them, the following ones are considered of interest in this document: competency in land, coast and urban planning; tourism; production, distribution and transmission of electricity; fishing; agriculture and livestock; and environmental protection (BOE, 1981). It should be noted that the competency of environmental protection refers to any further development of the basic regulations imposed by the central government.

The fact that the Galician government can enforce measures to guarantee the environmental protection in the region, and also its control over the sectorial regulations of numerous branches of the Galician economy, highlights the relevance of the calculation of the environmental impacts at a regional level, since policies aiming at their mitigation can be applied at the same regional scale.

2.1.4 Economy

This section has been split in three subsections, detailing first the main production activities located in the region and their economic relevance, then focusing in the contribution of the touristic sector to the regional economy, and last analysing the Galician consumption activities.

2.1.5 Production activities

Being a rural, coastal area, Galicia has traditionally been dependent on the primary sector, which still plays a more important role in the regional economy than in the rest of Spain (Figure 8). The Galician Gross Domestic Product reached $5.68 \cdot 10^{10}$ € in 2015 (IGE, 2017a).

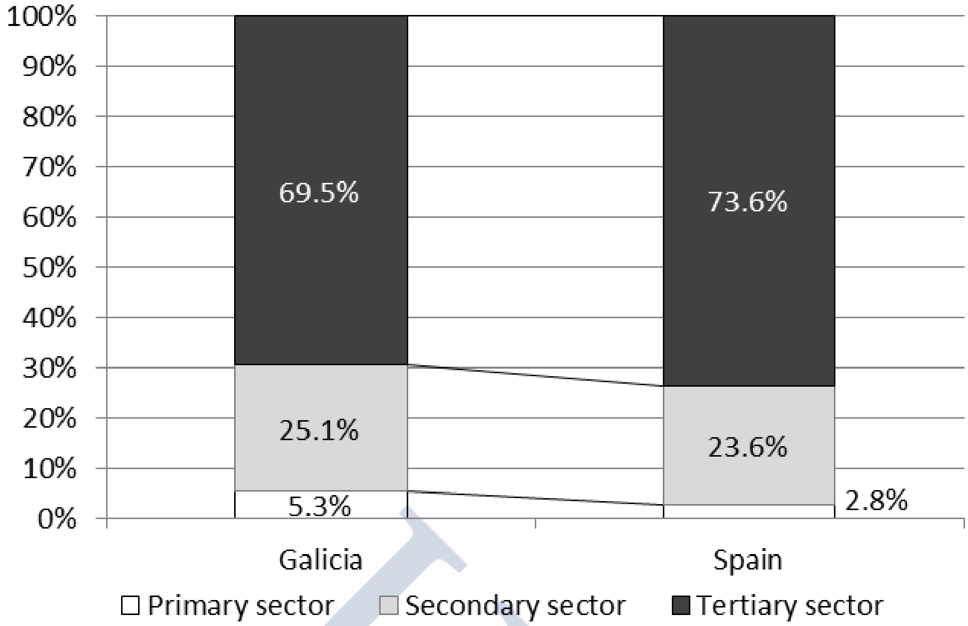

Figure 8: Distribution of the Galician and Spanish Gross Added Value among productive sectors in 2015 (IGE, 2017a; INE, 2018a).

The Gross Value Added (GVA) of the Galician primary sector is, in turn, split as follows (IGE, 2017a): Agriculture and livestock provide the highest share of its value (64%), followed by fishing (25%) and forestry (11%).

Within the agricultural sector, the most abundant crops are forage plants, which occupied 63% of the agricultural land available in 2015, followed by legumes (9%) and cereals (8%). Among forage plants, grasslands and maize represent the highest share of the annual production (65% and 32%, respectively) (MAPAMA, 2016). Within the livestock sector, the most abundant cattle are pig (48%) and bovine animals (42%). In 2015, they produced $4.43 \cdot 10^5$ t of meat (of which 35% were beef and 19% pork), and $4.43 \cdot 10^5$ m^3 of milk (almost 100% cow milk). In 2016, Galician milk production represented 33% of the Spanish one, thus highlighting the relevance of this commodity in the region (MAPAMA, 2016).

The fishing sector is also one of the most productive ones in Spain, since 48% of the Spanish fishing fleet is registered in the region (MAPAMA, 2016). The Galician ports unloaded $1.88 \cdot 10^5$ t of fish in 2016 (Pesca de Galicia, 2018), representing 21% of the Spanish captures (MAPAMA, 2017).

Last, a substantial wood production is also harvested from the Galician forests, reaching $7.38E \cdot 10^6$ m^3 in 2014 (47% of the Spanish production), which were split into broadleaved species (mainly eucalyptus, 56%) and coniferous species (mainly pines, 44%) (MAPAMA, 2016).

The main contributors to the GVA of the secondary sector (25.1%, Figure 8) are the Galician manufacturing industries (54%), followed by the building sector (27%) and by electricity generation (16%) (IGE, 2017a).

The GVA of the manufacturing sector is split among numerous industries, of which food processing and vehicle manufacturing stand out (Figure 9).

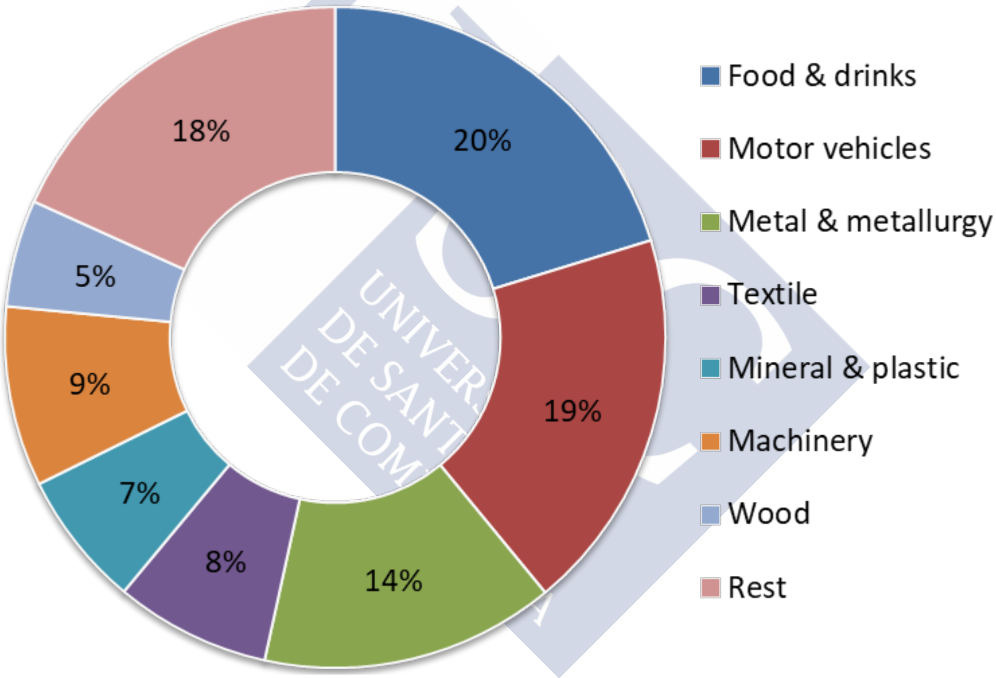

Figure 9: Distribution of the GVA of the Galician industrial sector in 2015 (IGE, 2017a).

The Galician food processing industry is made of numerous facilities of various sizes spread throughout the entire region, devoted mainly to process the fish and agricultural products obtained in Galicia (SABI, 2018). However, not all sectors are that divided, since Galicia also hosts several high turnover manufacturing industries: a textile factory, a metallurgic industry, a timber processing one and a car manufacturing company and its numerous suppliers.

Regarding energy production, Galicia is a net exporter of electricity to the rest of Spain: in 2016 the region produced 30,500 GWh (12% of the Spanish total), of which more than 10,000 were exported (REE, 2018). The region has also a cleaner electricity mix than the country average, mainly due to hydropower and windpower generation (Figure 10).

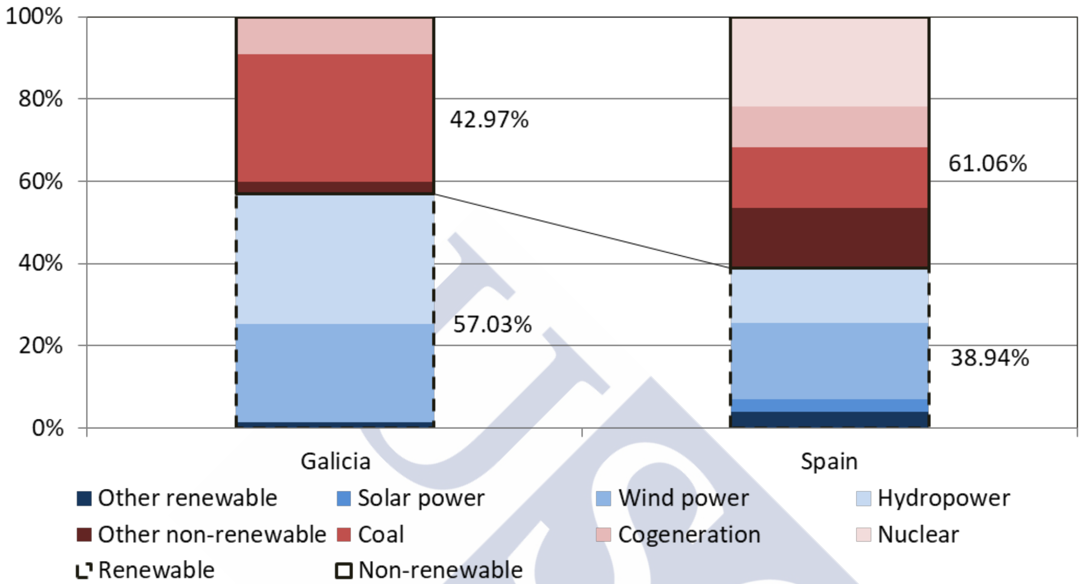

Figure 10: Galician and Spanish electricity mix in 2016. Adapted from (REE, 2018).

Last, the GVA of the tertiary sector (69.5%, Figure 8) is quite split among its numerous comprised services, being vehicle selling and repairing (20%), real estate (14%) and health services (11%) its main contributors (IGE, 2017a).

2.1.6 Tourism

Mainly due to the pilgrimage to Santiago de Compostela, but also to the international recognition of some of its monuments (UNESCO, 2018a, b, c) and natural landscapes (The Guardian, 2007), Galicia is increasingly becoming a touristic destination.

In 2016, Galicia registered more than 10 million touristic overnights, representing 2.2% of the total Spanish ones. The number of overnights in Galicia increased by 9% when compared to 2015, and also the number of visitors received (who spent at least one night in the region), which reached 4.9 million and rose by 7% when compared to 2015. Among those visitors, almost 300.000 were registered as pilgrims (Turgalicia, 2018).

The Gross Domestic Product (GDP) generated by the Galician touristic sector reached $6.02 \cdot 10^9$ in 2014, representing 11.1% of the total GDP of the autonomous community (Exceltur, 2016).

2.1.7 Consumption activities

The differences found between the Galician region and Spain (especially in terms of economic activities) are also reflected in the consumption patterns of its inhabitants. The expenditures of the Galician inhabitants reached 10.549 € in 2015, being 4% lower than the Spanish average (INE, 2018b). Significant differences are found between the different expenditure categories (Figure 11): the Galician inhabitants spend more money in food, and less in housing (which includes the dwelling itself but also energy and water consumption) and leisure (hotels, restaurants and entertainment).

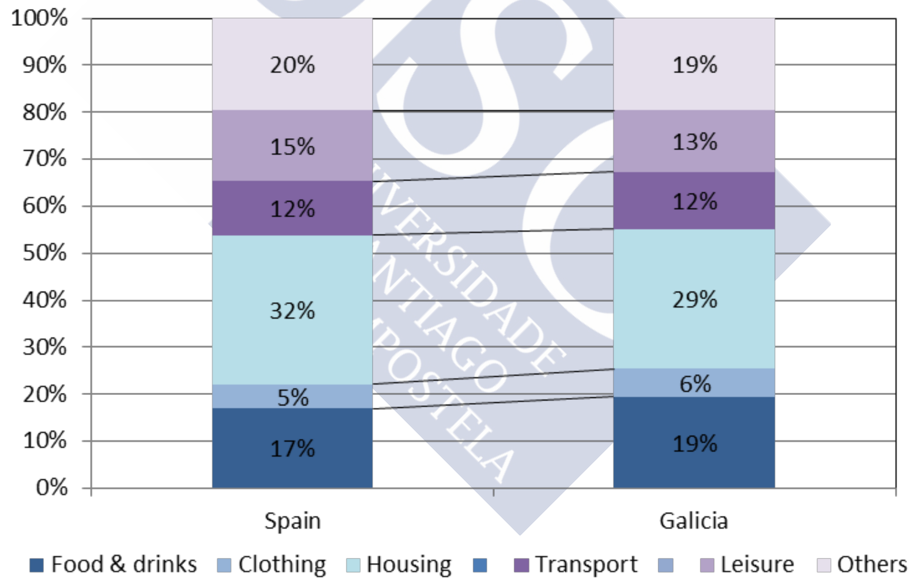

Figure 11: Distribution of the yearly expenditures of a Galician and a Spanish inhabitant (INE, 2018b)

Regarding food and beverage consumption, the Galician inhabitants allocate the highest expenditures to meat (23%) and fish (12%), bread and cereals (13%) and milk and its derivatives (11%). Within housing, the Galician inhabitants spend the highest amounts of money in the rent (63%), followed by electricity (9%) and heating (6%).

2.1.8 Environment

As already mentioned, the Galician government possesses the competencies to establish environmental regulations in the area. The regulations, plans and programmes available (Xunta de Galicia, 2018c) focus on the main concerns in the area: water related issues, greenhouse gas emissions, waste management and forest fires.

Regarding general water quality, and following the requirements of the European Water Framework Directive (WFD, (European Comission, 2000)), the Galician government recently updated the Galician Hydrological Plan (Augas de Galicia, 2016), which establishes a register with protected areas, inventories water pressures (punctual and diffuse sources of pollution), and establishes a control programme to evaluate the chemical and ecological conditions of the Galician waters. In 2015, it was found that the ecological status of 23% of the Galician superficial water bodies was "less than good"[10]. The plan also includes the approval of measures to reach the objectives set by the WFD, such as the Galician wastewater treatment plan (Augas de Galicia, 2000). Moreover, and even though the Galician precipitations reach an annual average of 1300 mm, the region is sometimes affected by water shortages, due to the uneven distribution of the precipitations throughout the year. Thus, the Galician government also created a water shortage plan (Augas de Galicia, 2013), aimed at mitigating its effects both on the population and on water bodies.

Galicia emitted almost 29 $MtCO_2e$ of greenhouse gases in 2015 (8.6% of the Spanish GHG emissions). Its main contributor was the energetic sector (41%). More specifically, the direct emissions of coal burning facilities producing electricity reached over 10 $MtCO_2e$ in 2015 (Xunta de Galicia, 2018b). The Galician government elaborates reports about climate change in the region every three years, where the GHG emissions are quantified, their effects on climate, hydric resources and ecosystems are analysed, and the measures aimed at tackling its effects are summarized (Xunta de Galicia, 2018a). The latter are classified into three categories: observation, research and adaptation (e.g. biodiversity monitoring, weather observation); reduction of GHG emissions (public aid for companies implementing environmental programmes, renewal of energy systems in public facilities); and sensitization and training (media campaigns, educational programmes) (Xunta de Galicia, 2016b).

[10] The ecological status is a criterion defined in the European WFD, which accounts for biological, hydromorphological, and physico-chemical conditions of waters (European Comission, 2000).

Concerning waste management, all Spanish Autonomous Communities need to adapt to the 2016-2022 Spanish Waste Framework (MAPAMA, 2013), conceived following the EU Waste Directive (European Comission, 2008), and which sets targets for recycling and reuse of materials that need to be adopted by the Autonomous Communities (e.g. by 2020, 50% of the urban waste must be sent for reuse and recycling). The Galician government has thus approved an urban management plan (which splits the aforementioned 50% among the different waste fractions in the community (Xunta de Galicia, 2011, 2016a)). Similarly, the Galician government has approved plans and programmes aimed at the prevention (Xunta de Galicia, 2013a) and management (Xunta de Galicia, 2016c) of industrial waste, and at the management of construction and demolition waste (Xunta de Galicia, 2013b).

Regarding forest fires, Galicia suffered 42% of the blazes occurred in Spain in the 2001-2010 decade, which in total burnt over 288 thousand hectares of forest (MAPAMA, 2012). The Galician government approves annually a plan for the prevention and defence against forest fires (Xunta de Galicia, 2017c), stablishing the yearly objectives regarding the maximum number and size of the fires, and also the high-risk season and the firefighting media available. October 2017 was an especially severe period, in which 49 thousand hectares were burnt, of which over 23% belonged to areas of special protection from the Natura 2000 network (Xunta de Galicia, 2017b). The Galician government has thus announced new measures of prevention and firefighting (Xunta de Galicia, 2017a).

2.2. Galician LCA based studies

A recent bibliometric study (Hou et al., 2015) found out that the University of Santiago de Compostela (Galicia) ranked 6th among the worldwide institutions in which more LCA studies were carried out. It is thus not surprising that numerous LCA studies focus on the region. However, none of them has so far determined all the impacts linked to the area. A brief summary of them is presented here, classified based on their coverage.

2.2.1 Product studies

Numerous LCA based studies have determined the environmental impacts of Galician food and beverage products. Some examples are beer (Hospido et al., 2005), wine (Vázquez-Rowe et al., 2012; Villanueva-Rey et al., 2014), milk (Hospido et al., 2003; Iribarren et al., 2011a), cheese (González-García et al., 2013), several fish products (Hospido and Tyedmers, 2005; Hospido et al., 2006;

Iribarren et al., 2010a; Vázquez-Rowe et al., 2010, 2011; Vázquez-Rowe et al., 2013) and pork (Noya et al., 2017). This individual studies, that address either one (the carbon footprint) or various environmental impacts, focus on the food manufacturing sector, one of the most relevant of the Galician economy, as already mentioned.

Not only food products have been analysed in Galicia from an LCA perspective. Wastewater treatment (Gallego et al., 2008; Hospido et al., 2008; Hospido et al., 2012; Lorenzo-Toja et al., 2015; Rodriguez-Garcia et al., 2011) and forest and forest-based industry (Gonzalez-Garcia et al., 2009; González-García et al., 2011) products have also been evaluated.

2.2.2 Sectorial studies

The LCA methodology has been applied to calculate the carbon footprint of the Galician fishing sector, a pillar of the Galician economy. The study determined that the CF of the whole sector exceeds 188,000 tCO_2e/y (Iribarren et al., 2010b, 2011b). This is, however, the only environmental impact calculated there, and thus the authors only apply their bottom-up methodology to one of the numerous economic sectors of the region.

2.2.3 Regional studies

To the best of my knowledge, no complete LCA based studies, where several environmental indicators have been determined, exist so far for Galicia.

However, a recent study has calculated the carbon footprint of the Galician consumption in 2010 (Ivanova et al., 2017). The study was carried out within the framework of the Glamurs project[11] (Glamurs, 2018), in which this indicator was calculated for all the European regions, and the results were used to evaluate how choosing sustainable lifestyles would affect the emissions in some of them.

To do so, the authors used the Exiobase MRIO database (Wood et al., 2015), as already done by Ivanova et al. (2016) for all countries

[11] The Project GLAMURS (Green Lifestyles, Alternative Models and Upscaling Regional Sustainability) aims at studying sustainable lifestyles and at developing policies to support transitions to sustainable lifestyles. http://glamurs.eu/

included in the database, but following the refined methodology used by Steen-Olsen et al. (2016). According to their results, the CF of a Galician inhabitant reached 11.1 tCO2e/y, and its main contributors were services (31%), food (23%) and mobility (23%) (Figure 12).

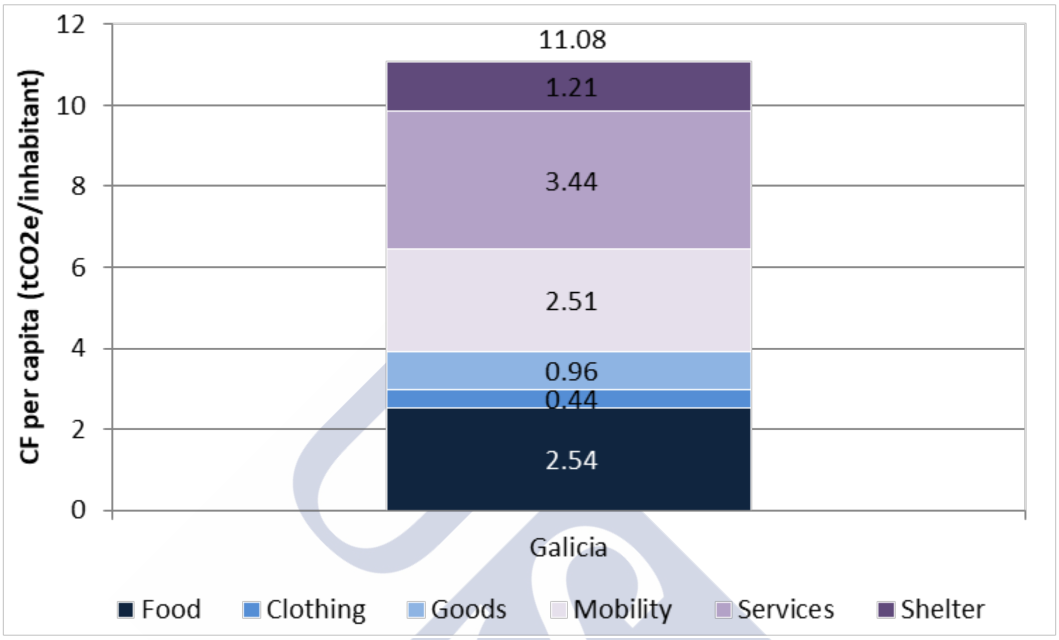

Figure 12: CF results of a Galician inhabitant. Adapted from Ivanova et al. (2017)

To carry out that study, it was necessary to combine Spanish data (from Exiobase) with Galician data (the consumption expenditure vector y, named CES). To make the combination possible, several modifications were required: to convert CES consumer prices into producer prices, to accommodate CES consumption categories to Exiobase ones, to account for price variations due to the use of different years, and even to consider the low representativeness of some categories of the regional consumption statistics.

Thus, and even though the study is very complete, the required assumptions and conversions probably increase the uncertainty of the results. Moreover, and being an IO based study, it is expected to suffer from the usual aggregation issues linked to that methodology.

Focusing in one impact category only, a PhD thesis calculated Galician specific terrestrial and aquatic eutrophication characterisation factors (Gallego, 2008), and used them to calculate the following normalisation values: 282 t N/y into soil for the former and 35,549 t PO_4^{3-}eq/y into water for the latter.

In any case, a complete dataset of impacts (i.e. normalisation factors) for Galicia is lacking, and its carbon footprint available only includes consumption impacts evaluated from an IO perspective only.

Chapter 3: Objectives and structure

3.1. Objectives of the thesis

The main objective of this thesis is to obtain the normalisation factors (NFs) of all the production and consumption activities occurring in Galicia, using the territorial LCA methodology. These are expected to be the first complete normalisation datasets calculated for the autonomous community, as well as the first ones obtained with this methodology, and thus they can be used as a reference in future LCA studies of Galician based products or processes.

The application of territorial LCA to such a large region raised problems related to the *intra* double counting of impacts, since many Galician products are used again as raw materials within the community. Thus, the methodology has been improved by means of a double counting solving procedure, which can ease its application in subsequent studies of large regions.

One of the impact categories included in the Galician NFs is the carbon footprint (CF). Due to the relevance of this indicator, reduction measures have been proposed and further attention has been paid to its calculation: in order to facilitate the updating and refinement of the CF calculation, different methodological alternatives to territorial LCA have been tested, seeking to reduce calculation times and to guarantee the representativeness of the results.

Thus, the application of territorial LCA to Galicia, its improvement and its comparison to different methodological alternatives for CF determination are also central objectives of the thesis.

Linked to the CF determination and as already mentioned, the calculation and tackling of that impact alone can lead to the switch of the environmental burdens into other areas. A frequent measure for carbon compensation is afforestation, which can increase water depletion. Thus, another objective of this thesis is to propose a methodology to choose the best location for compensation projects and to evaluate how they affect water footprint.

Last, and as further detailed in the next subsection, LCI data of all Galician production and consumption activities was required to apply the territorial LCA methodology and to fulfil the aforementioned objectives. Thus, several LCA studies of Galician based products have been carried out within the framework of this thesis, whose environmental assessment can be regarded as an intermediate objective of this project.

3.2. Structure of the thesis

This thesis consists of seven papers, which are linked to each other as shown in Figure 13.

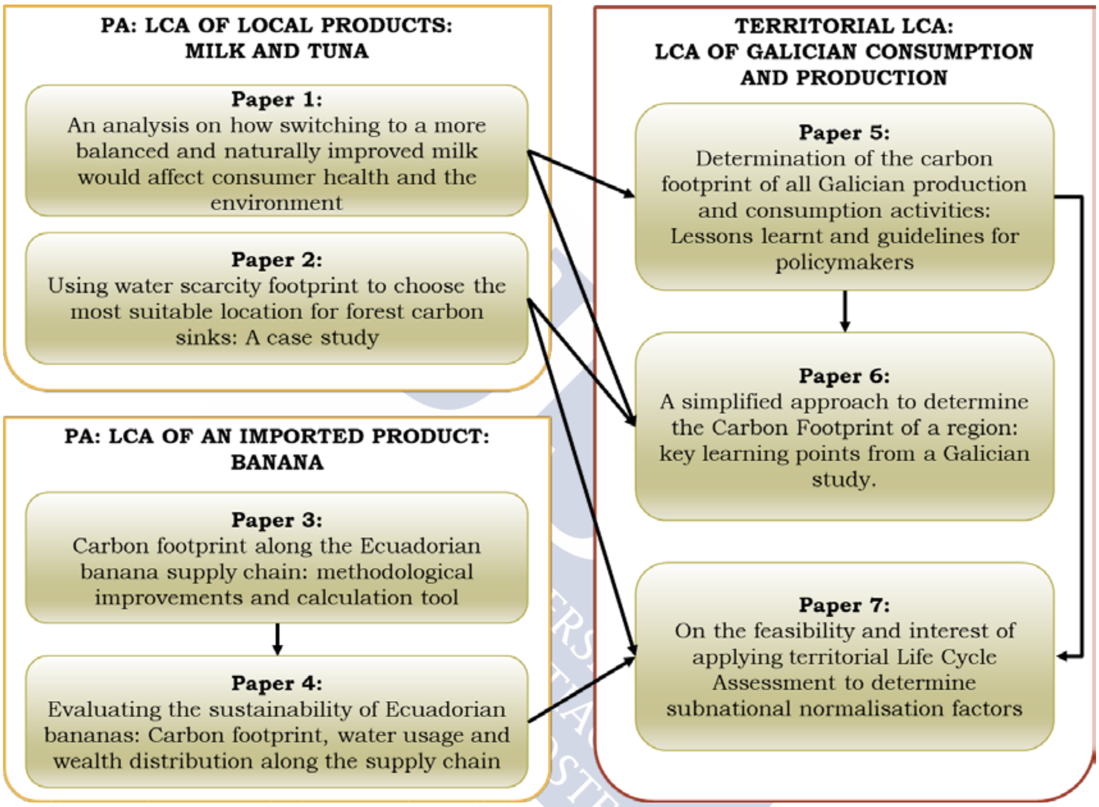

Figure 13: Structure of the thesis and connections among the resulting articles.

The Galician normalisation factors have been calculated in paper 7, while the detailed results of the carbon footprint (including mitigation measures) are detailed in paper 5, and the comparison of different methodological alternatives to calculate this indicator is shown in paper 6.

Before applying territorial LCA to the region, it was necessary to create Life Cycle Inventories of all the consumption and production activities taking place in the region. To do so, local statistics (i.e. activity descriptors) and inventory data from numerous individual LCA studies have been combined.

Thus, this thesis also includes three LCA studies of individual products consumed or produced in Galicia. The product consumed is Ecuadorian banana, while the local ones are cow milk and canned tuna produced by two important companies in the region. The first is an imported product of global distribution, while local products represent two of the most relevant sectors in Galicia: fishing and livestock. The calculation of the environmental impacts of the three products was the starting point of this thesis (papers 1 to 4), and their inventory data and results have been used either to obtain or to test the Galician carbon footprint and normalisation factors.

More specifically, the milk production inventory data (paper 1) has been used as part of the LCI of the Galician productive activities, required to obtain both the Galician CFs and NFs. The canned tuna inventory (paper 2) has been used to calculate the CF of Galician production activities when following one of the alternative methodologies to territorial LCA tested (paper 6). Last, the LCA results of both canned tuna production and banana consumption (papers 3 and 4) have been used to verify the robustness and applicability of the corresponding Galician normalisation factors.

Paper 2 also provides a preliminary approach to choose the best possible location for carbon compensation projects.

In order to help the reader's understanding, the main contents of each paper are briefly summarized below.

Paper 1 calculates the carbon and water footprints of two brands of Galician milk, from a cradle to gate perspective. The brands are compared in terms of both environmental indicators, but also from the consumer health point of view, as one of them is characterised by an improved composition.

> ***Roibás, L.**, Martínez, I., Goris, A., Barreiro, R., Hospido, A., 2016. An analysis on how switching to a more balanced and naturally improved milk would affect consumer health and the environment. Science of the Total Environment 566–567:685-697.*

Paper 2 calculates the CF of canned tuna production from a cradle to gate perspective, and it evaluates how its compensation can affect other environmental indicators, in particular the water footprint.

> ***Roibás, L.***, *Cuevas, A., Vázquez, M.E., Vilas, M., Hospido, A., 2018. Using water scarcity footprint to choose the most suitable location for forest carbon sinks: A case study. Sustainable Production and Consumption 16:1-12.*

Paper 3 determines the carbon footprint of Ecuadorian bananas consumed in Spain, from a cradle to grave perspective, and **Paper 4** complements its results with the water footprint and economic analysis of the product throughout its supply chain.

> ***Roibás, L.***, *Elbehri, A., Hospido, A., 2016. Carbon footprint along the Ecuadorian banana supply chain: methodological improvements and calculation tool. Journal of Cleaner Production 112:2441-2451*

> ***Roibás, L.***, *Elbehri, A., Hospido, A., 2015. Evaluating the sustainability of Ecuadorian bananas: Carbon footprint, water usage and wealth distribution along the supply chain. Sustainable Production and Consumption 2:3-16*

Paper 5 calculates the carbon footprint of all Galician production and consumption activities using the territorial LCA methodology, which is in turn improved to avoid double counting issues. Measures aimed at reduce GHG emissions linked to the region are also proposed.

> ***Roibás, L.***, *Loiseau, E., Hospido, A., 2017. Determination of the carbon footprint of all Galician production and consumption activities: Lessons learnt and guidelines for policymakers. Journal of Environmental Management 198:289-299*

Paper 6 starts from the previous results and evaluates different methodologies to calculate the Galician consumption and production CFs. A multi-criteria analysis is applied to choose the optimal methodology to use in subsequent studies in this or other regions.

> ***Roibás, L.***, *Loiseau, E., Hospido, A., 2018. A simplified approach to determine the Carbon Footprint of a region: key learning points from a Galician study. Journal of Environmental Management 217: 832-844.*

Paper 7 calculates the normalisation factors of both Galician consumption and production activities, using the improved territorial LCA methodology obtained in paper 5. The NFs are tested by evaluating two of the previously presented case studies: banana consumption (papers 3 and 4) and canned tuna production (paper 2).

***Roibás, L.**, Loiseau, E., Hospido, A., 2018. On the feasibility and interest of applying territorial Life Cycle Assessment to determine subnational normalisation factors. Science of the Total Environment 626:1086–1099*

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Section 4: Territorial LCA of Galician production and consumption

Paper 5:

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Paper 6:

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Journal of Environmental Management 217: 832-844.

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Paper 7:

On the feasibility and interest of applying territorial Life Cycle Assessment to determine subnational normalisation factors.

Roibás, L., Loiseau, E., Hospido, A., 2018.

Science of the Total Environment 626:1086–1099

https://www.sciencedirect.com/science/article/pii/S0048969718301499

Section 5: Discussion and conclusions

Chapter 4: Discussion

This chapter discusses the main findings of this thesis, and it is further split into three subsections. The first one is a general discussion meant to ensure the consistency of the different sections of this document, and thus the research needs tackled in each paper are linked to each other, and to the thesis objectives. Territorial LCA is the methodological core of this thesis, but some modifications have been made to the approach in this document. Thus, the second subsection compares the approach followed here to that of the original territorial LCA methodology, by identifying the main differences between both of them. Last, a third subsection groups the ways forward in which the results and procedures included in this thesis could be improved.

4.1. Consistency of this document

Sections 2 and 3 of this document present PA based LCA studies of food products, whose data was later used in section 4 to obtain both the carbon footprint and the normalisation factors of all Galician activities. This section specifies which data of those first studies (papers 1 to 4) has been used in the last three (papers 5 to 7) to obtain the Galician impacts. In any case, these first PA based studies were essential for the author to get familiar with the LCA framework and with conventional LCAs, necessary for the subsequent deepening into IO and hybrid approaches, such as the territorial LCA used in section 4.

The first step to calculate both the Galician CF and its NFs was to obtain LCI data for all of them. Within the production activities, and as detailed in section 1 of this document, the primary sector plays a major role in the Galician economy. Among the activities of the primary sector, livestock (and the related agriculture) and fishing stand out. Thus, PA based LCI data obtained in this thesis have been used to characterise the Galician primary sector, when possible.

A thorough study of the environmental (and health) impacts of milk production in Galicia was carried out within the framework of this thesis. In that study, LCI data was obtained for Galician conventional milk and also for a regional premium brand (Unicla). Average LCI data from conventional farms has been used to characterise the Galician raw milk production sector, and average LCI data from both types of farms has been used to characterise the two main crops grown in the region: grass and forage maize. It should be noted that the original LCI data from the milk study (paper 1, where Ecoinvent v2 was used) has been updated to use Ecoinvent v3.1 in the Galician LCIs (papers 5 to 7), which allows considering not only direct but also indirect blue water use throughout the life cycle of milk. When evaluating the Galician NFs, only blue water has been included in the inventories, since the grey water is not consistent with the LCA framework, and LCI data of green water is usually not available in PA databases. Milk inventories were first meant to calculate carbon and water footprints, but they have been completed afterwards to include other environmental flows (e.g. NH3 emissions to air and metal and pesticide depositions to soil), which do not affect CF or WF but other indicators conforming the Galician NFs. It should be noted that, even though Unicla LCI data for milk production has not been used to characterise raw milk production in Galicia (due to the insignificant share of the brand in the total production), the improvements made to the cows' diet to obtain the brand, leading to lower GHG emissions, can be seen as a pathway to the diminishing of the regional impacts. The methodological choices used in the milk study (biophysical allocation as recommended by the IDF, and the nutrient leaching factors for N (30%) and P (3%), recommended by the IPCC and the WFN, respectively) have been kept here. These choices, considered the most appropriate by the authors, largely affected WF and CF results in the milk study, and thus they are also expected to affect the impact results at the Galician scale. Last, it should be noted that the milk study has been recently updated and broadened including more farms (up to 8 conventional farms), and refined by using IPCC tier 2 methodologies. This updated study was meant to certify the GHG emissions of both types of milk, and as a result of that study, the CF reduction percentage of Unicla milk is now included in its packaging[1]. The updated LCIs, leading to an 11% increase of the CF of conventional milk, could be used to update the current Galician production LCIs, and thus the production CF and NFs.

[1] http://www.elcorreogallego.es/galicia/ecg/certificado-huella-carbono-leche-unicla-cooperativa-clun/idEdicion-2017-09-23/idNoticia-1074415/ https://www.agrodigital.com/2017/09/25/clun-primera-lactea-que-certifica-con-aenor-la-huella-de-carbono-de-la-leche/

Within the fishing sector, the carbon and water footprints of canned tuna production were also determined within the framework of this thesis (paper 2). The study, carried out in 2014, updated a previous one from 2005 and it was meant to evaluate how the impacts had evolved due to the changes in the raw material provision and production processes. The LCI data of the new study has not been used to characterise the Galician fishing sector, since only those species sold at the port markets are accounted for, due to the lack of data. Among them, only those representing more than 1% of the weight of the captures have been considered. Tuna is rarely sold at the port market (in 2017, it only represented 0.2% of the total sales there) but taken to processing facilities, where it is converted into different final products. Thus, the LCIs of the fish sold at the port market have been taken from Vazquez-Rowe (2012), and fresh tuna has been excluded. Once canned tuna carbon and water footprints were updated, the effects that compensating GHG emissions through afforestation could have on water scarcity were evaluated. To do so, a simplified approach was followed to calculate the WF of the compensation project, and it was proven that this indicator could be useful to choose the most suitable location for afforestation. This approach, which needs to be further refined, could be considered if the Galician GHG emissions were to be compensated through afforestation.

Both UHT milk and canned tuna are key industrial processes from the food manufacturing sector in Galicia. Since mass activity descriptors (i.e. physical amounts of each product manufactured) were not available for all the Galician industries, it was decided to model the whole manufacturing sector using IO data when following the territorial LCA based approach (papers 5 and 7). Thus, the LCI data of canned tuna and UHT milk have not been used to calculate the Galician production impacts when following this approach. However, when several alternatives have been compared to simplify the CF calculation (paper 6), and PA has been used to characterise the manufacturing activities, LCI data for the following processes coming from both Galician studies were used: UHT milk, fodder, canned tuna and tinplate cans manufacturing. All LCI data from both milk and tuna studies (papers 1 and 2) has been updated to Ecoinvent v3.1

when building Galician inventories, to properly account for blue water depletion.

When using an approach based on territorial LCA to evaluate the CF and the NFs of the Galician consumption (papers 5 and 7), no PA based inventories have been used, since only economic values for household expenditures were available at the regional level. Thus, the LCI data obtained in this thesis for banana consumption (papers 3 and 4) has not been used to calculate the Galician consumption impacts. However, and being a comparative case study (organic versus conventional banana), it has been decided to use it to test the robustness of the consumption NFs obtained using territorial LCA. Similarly, the LCI data of the two canned tuna supply chains (2005 and 2014) has been used to test the robustness of the production NFs obtained using territorial LCA. Both case studies have been chosen since none of them had been used to obtain the LCIs of the Galician consumption or production when using territorial LCA, and thus they are considered independent from the NFs obtained.

Even though the organic and conventional banana inventories have not been used to characterise the Galician consumption, special care was taken to obtain them, since they were meant to test the Galician NFs and they could also be used in subsequent refinements of the territorial LCA approach (see section 4.3). Thus, efforts were made to obtain as precise impacts as possible: the nitrogen emission factors arising from fertilised soils were adapted to the Ecuadorian climatic conditions, and modifications were made to consider different transport characteristics. First, a procedure to account for different load percentages when calculating transport impacts was created, and second, the Ecoinvent v2.2 inventories used at the time were modified to account for the burdens linked to refrigerated transport. The newest versions of Ecoinvent (from v3.2 on) already include different possibilities for refrigerated transport but, to the best of my knowledge, it is still not possible to account for different load percentages. The first CF study was then completed with water footprint data (again, only the blue water component has been incorporated in the LCI data used to test the Galician NFs) and with economic results, to obtain a complete picture of the sustainability of banana consumption.

A type B territorial LCA approach has been followed to compute LCI data of all the consumption and production activities occurring in Galicia. The former correspond to both the activities of the Galician inhabitants and those of the tourists who visit the region, and the latter correspond to the productive activities taking place in the region. Both consumption and production activities were further split: five consumption subactivities are considered, and eight production ones, both following the classification of Loiseau et al. (2013). Being a life cycle approach, LCI data include inventories of the whole life cycle of all the products consumed and produced in Galicia, regardless of where the upstream impacts occur. To characterise the inventories of each activity, PA data was used when available (e.g. from the Galician milk study), but IO data from the USEIO database was also required for some activities (i.e. food, goods and services in consumption, and manufacturing in production). Given the broad scope of the study, double counting issues arise when applying the original territorial LCA approach to calculate the impacts of both the Galician consumption and production, and a procedure had to be implemented to solve this issue. Within consumption activities, it was solved by manually modifying PA LCIs to exclude the flows already accounted for in IO based LCIs. Within production, a consumer responsibility approach was chosen (i.e. the activities far downstream in the supply chain bear the largest share of the impacts) based on economic data of the Galician inter-industry flows, taken from the Galician IO matrix (IGE, 2017). Once LCI data were obtained and these double-counting solving procedures conceived, the carbon footprint of all Galician consumption and production activities was calculated (paper 5). Hotspots were identified (i.e. housing (electricity and heating) and food (animal based products) in consumption and electricity and food manufacturing in production) and suggestions were made to lower the GHG emissions of both the Galician consumption (installation of solar panels and lowering the consumption of livestock-based foodstuff) and production (shifting to more renewable sources of electricity and lowering livestock emissions). The main limitations of the applied procedure to calculate the CF were also acknowledged (i.e. data gaps, large time consumption requirements, low temporal, geographical and technological representativeness of the USEIO database) and further improvement proposals were pointed at (see section 4.3).

Once the Galician CF was calculated following the territorial LCA approach, it was observed that the complexity of its application (mainly due to the data gaps and the large data gathering requirements) may not be worthy to evaluate just one impact category, and that alternative, simpler approaches could be used instead. Thus, the aforementioned CF results were split into PA based results and USEIO based ones, and they were compared to those obtained with other SRIO and MRIO based approaches (paper 6). The objective was to reach a compromise between the high representativeness of the results and the simplification of the procedure. Among the IO databases used, the Galician IO matrix (SRIO), the World Input Output database (MRIO) and the Exiobase database (MRIO) were compared. Different assumptions were required when applying each approach, looking for their simplification, and the CF results obtained with each of them were then compared in terms of reliability, completeness, temporal and geographical correlation, applicability and consistency. It was concluded that the Galician IO matrix (also named MIOGAL) was the best option to obtain reliable CF results with low calculation efforts, and that it could be used for subsequent, simplified territorial LCA studies in this or other regions where IO tables are available. The CF results obtained with the MIOGAL matrix did not differ much from those obtained with the territorial LCA approach (less than 4% differences for consumption and 1% for production), even though they were differently split into subactivities. Last, it was acknowledged that the simplified methodology could still be improved (see section 4.3), mainly because of the use of a SRIO matrix, which probably leads to the underestimation of the CFs: a 25% underestimation of the consumption CF was found when SRIO and MRIO approaches were compared in Spain, and our results are much lower than those found by Ivanova et al. (2017), using a MRIO approach for the Galician consumption.

Last, the LCI data gathered following the territorial LCA approach was used again to obtain the Galician consumption and production external normalisation factors, using the ReCiPe midpoint characterisation method and applying again the double counting solving procedure (paper 7). Since these NFs were obtained following a life cycle approach, their reference system is expected to be consistent with that considered in the LCA studies of individual products, either produced or consumed in Galicia. The study was the first application of the territorial LCA approach to the obtaining of normalisation references, and also the first calculation of those references at the subnational level. Fifteen NFs for the Galician consumption and production were made available, which were split into its main contributing activities and substances. In practice, the Galician NFs are the annual impacts of both consumption and production activities, and thus the results obtained were also used to identify environmental hotspots and to propose mitigation actions. The hotspots found were consistent to those already found for the Galician CF (i.e. food and housing in consumption and electricity and food manufacturing in production), and thus the mitigation measures pointed in the same direction (use of cleaner energy sources and the reduction of the consumption of livestock based products and of the emissions from their production). Both Galician normalisation datasets were tested in the two comparative case studies included in this thesis: the consumption NFs were applied to the impact results of conventional and organic banana consumption, and the production NFs were used to evaluate the impacts of the former and the current canned tuna supply chain. The normalised results obtained using the Galician NFs were compared to those calculated with different reference systems, and some differences were found in the relevance of the impact categories, even though they did not significantly alter the conclusions of the case studies. The results point at the usefulness of these additional normalisation references, so as to allow conducting sensitivity analysis in LCA studies and to test the robustness of their conclusions, as recommended by the corresponding standard (ISO, 14044:2006). Several drawbacks of applying territorial LCA to obtain normalisation factors were pointed at, apart from those already mentioned for the CF determination (i.e. data gaps, time requirements and use of the USEIO database). So, several other sources of uncertainty were identified when calculating the remaining NFs:

i) the lack of substances in the inventory data;

ii) the uncertainty of the characterisation factors; and

iii) the inconsistencies found between the USEIO LCIs and the PA (mainly Ecoinvent based) LCIs.

Among the latter, the different modelling approaches used in both data sources (i.e. the inclusion or exclusion of long term emissions, and the different modelling of pesticide emissions), the different substance coverage and the lack of differentiation among generic substances in some inventories (i.e. the use of generic flows grouping substances having different characterisation factors such as *NMVOCs* or *energy consumption*) were highlighted. Thus, it was concluded that territorial LCA is a promising approach for the determining of NFs, but that some improvements could still be made to the procedure (see section 4.3).

4.2. Comparison to the original territorial LCA approach

A procedure based on a type B territorial LCA has been used to calculate the carbon footprint and the normalisation factors of all Galician consumption and production activities. Our procedure is based on territorial LCA, since the same classification of activities for consumption and production, the same activity descriptors, and an identical hybrid approach (combining PA data with LCI from the USEIO database) have been used here. However, several differences aimed at the refinement of the methodology exist between our approach and that of Loiseau et al. (2013):

- As already mentioned and given the large size and the certain self-sufficiency of Galicia, a novel double counting solving procedure had to be implemented here, to ensure that the impacts of the Galician production activities were not accounted for twice.
- Moreover, several alternatives to calculate the CF of all consumption and production activities in a simpler way have been compared to the original hybrid one, and it was concluded that using the MIOGAL matrix could offer more consistent and representative CF results with a much lower time investment. Our approach could still be improved, and the possible measures to do so are detailed in section 4.3.

However, some of the original characteristics of the approach have not been used in this document:

- Territorial LCA proposes evaluating the land planning scenario of a certain territory, by taking into account the functions satisfied by it through several indicators. The application of the territorial LCA approach to Galicia was not meant to evaluate its land planning scenario or to compare it to future alternatives, and thus the vector of functions usually included in territorial LCA studies has not been made available here.
- Loiseau et al. (2014) propose to distinguish between direct (on-site) and indirect (off-site) impacts, which could clearly help local stakeholders to tackle environmental impacts, by differentiating which share of them arises directly from the territory under their control. Thus, a distinction between on-site and off-site burdens within the Galician impacts (both CF and the remaining annual impacts used as NFs) could be useful for local stakeholders, often interested by on-site impacts. This differentiation, however, was discarded in this document due to the long data and time requirements to distinguish between foreground and background processes in each LCI used. The author acknowledges that the results could thus be further improved by means of this differentiation. Moreover, this would act as the first step to spatial differentiation in territorial LCA, mentioned in the literature as one of the ways of improving the approach (Loiseau et al., 2018; Nitschelm et al., 2016). The differentiation between on-site and off-site inventory data is required to allow using regional-specific characterisation factors, which can improve the reliability of the impact results.

4.3. Ways forward

This section summarizes how the methodology used and the results obtained in this thesis could be improved. It is split into three subsections: the first one refers to the territorial LCA methodology, the second one focuses on the Galician NFs obtained, and the third one refers to the procedure to account for impacts on water scarcity caused by carbon compensation.

4.3.1 Territorial LCA

Type B territorial LCA can be regarded as an iterative approach, and thus once the first results are computed, they can be refined by using more detailed or representative LCI data (Loiseau et al., 2018). When applying the methodology in this document, a compromise was reached between the data quality requested and the time framework available, and thus the current results could still be improved. Several possible ways forward to do so are summarized here.

Territorial LCA is a tiered hybrid approach, combining PA inventories (when available) with IO based LCIs (otherwise). Hybrid procedures are believed to offer the most reliable results when compared to both PA and IO based alternatives (Majeau-Bettez et al., 2011; Pomponi and Lenzen, 2018). However, the tiered hybrid approach (being the simplest and more frequently used among the hybrid procedures available) suffers from two major drawbacks:

- The cut-offs linked to process analysis (since a PA based framework is used and thus some activities can unintentionally be left out of the assessment); and
- The double counting of the impacts (which has been solved here by means of the Galician IO matrix).

Using alternative hybrid methods not suffering from these issues is thus a possible way to improve the territorial LCA approach. The Path Exchange method (Lenzen and Crawford, 2009) or the Integrated Hybrid method (Suh et al., 2004) are currently considered the most consistent approaches for hybridisation (Crawford et al., 2018). Their application, however, remains scarce in the literature due to their high complexity and time and labour requirements (Crawford et al., 2018; Suh and Huppes, 2005). Thus, the integration of any of these more refined hybrid methods in LCA software would increase their usability and broaden their application (Crawford et al., 2018). Then, any of them could be more easily used to obtain the impacts linked to regional activities, such as the ones calculated here for both Galician consumption and production. In any case, using any of those approaches would not represent a refinement of the current results, but a totally different study.

When following the current approach, other methodological choices could be considered for the enhancement of the existing results. When applying territorial LCA along this thesis, both PA and the USEIO database have been used to obtain the LCI data required to calculate both the Galician CF and its NFs. The lack of representativeness of the USEIO database has been stated, and thus the use of a different IO database could represent a simple way of improving the existing results.

The very first steps in this direction were given when trying to refine the Galician CF results, by comparing different IO based approaches. A simplified methodology based on the Galician IO matrix was proposed. It was acknowledged, however, that the approach could still be improved: the Galician vector of environmental interventions had to be taken from Spanish statistics, due to the lack of Galician data; and the Galician matrix is a SRIO table, which affects the reliability of the impacts of imported products due to the Domestic Technology Assumption (DTA). It should be also noted that the comparison among IO approaches (and the conclusions drawn from it) was applicable only to the CF indicator, since data on GHG emissions is often readily available in EIO matrixes (or can be easily incorporated to them). Thus, the availability of a Galician based MRIO matrix, with sufficient regional-specific environmental flows to allow calculating NFs, and ideally consistent with the modelling approaches used in Ecoinvent, could significantly increase the accuracy of the normalisation results included in this study. From the lessons learnt during this thesis, a hybrid procedure combining MIOGAL results with PA based ones (i.e. substituting the USEIO data by that of the Galician matrix) seems to be the first option to go for to improve the current CF results.

PA based inventories are neither exempt from downsides (i.e. cut-offs and very large data requirements). However, the advantages of using this approach at the Galician scale are undeniable, since it is possible to identify which particular activity is responsible for each share of the environmental burdens, thus leading to better decision making and to a subsequent, quick refinement of the LCI data used, allowing the continuous improvement of the results. Moreover, the update and refining of the LCI data included in this study would now be much simpler and quick than its first compilation. Thus, PA based inventories should be kept and updated when possible, and their results can be compared to those obtained with IO approaches to identify (and solve) relevant cut-offs.

In this line, several refinements are still possible to improve the current PA inventories:

- The refining of the direct emissions included in Ecoinvent LCIs, by using actual Galician values when available (e.g. from the Galician GHG inventories)
- The further refinement of the generic inventories used, for which statistics could be found: e.g. crop inventories (other than forage crops) were taken from Ecoinvent and modified to properly consider land occupation and water use, but further refinements such as the use of actual fertiliser application rates (taken from surveys or recommendations for each crop grown in the region) could be carried out. The use of PA based inventories for some of the activities which have been so far modelled using IO data only. This could both serve to test the robustness of the current results and to allow identifying with high precision which activities are responsible for the environmental burdens. This could be done in a relatively easy way for food consumption, whose impacts were evaluated in this thesis based on the Galician expenditures expressed in euros. No Galician statistics of food consumption expressed in physical flows are available (only economic data is available for Galicia and Spain), but physical values exist for Spain, and thus food consumption mass flows could be extrapolated for our region. If done, PA based food inventories (such as the banana obtained here) could be used to obtain alternative results of the impacts of food consumption.
- The distinction between on-site and off-site (i.e. foreground and background) impacts could also lead to more efficient decision making based on the results of this thesis.

4.3.2 Normalisation factors

A recent study by Prado et al. (2017) proved that existing external normalisation factors are frequently not suitable for comparative LCA studies. When comparing the results of numerous case studies, they found that three impact categories had usually the highest normalised contributions in ReCiPe, regardless of the case study: freshwater ecotoxicity (FET), marine ecotoxicity (MET), and human toxicity (HT). Moreover, when other normalisation references were used (CML, TRACI), toxicity-related impacts were also highlighted throughout all the case studies.

The reason behind the prevalence of these toxicity categories is the underestimation of toxicity impacts in each reference area, due to the lack of emission data or of characterization factors. Thus, in practice, the use of these NFs in comparative studies could lead to biased decision making based on the toxicity results, which are characterised by a high uncertainty in all normalisation references.

The NFs provided in this document are both based on PA and IO data. PA inventories are not expected to suffer from the lack of toxic substances, but the USEIO data is, since it is based on data taken from the same sources as the TRACI NFs.

Two case studies have been evaluated here with the Galician NFs: banana consumption and canned tuna production. In the former, the dominant impact categories found with Galician NFs were toxicity categories coincident with those of ReCiPe (MET and FET), but their prevalence (the difference found with the remaining impact categories) was much lower than that of ReCiPe. In the latter, dominant categories were different when Galician NFs were used (MD and POF), while MET had the highest relevance when using ReCiPe. At the time, it was concluded that both the particular Galician characteristics (i.e. different human activities from Europe) and the use of different methodologies (i.e. a life cycle perspective here versus the production approach in ReCiPe) could explain the differences, but these new findings also point at the lack of completeness of the toxic inventories used in ReCiPe NFs.

It can be concluded that the Galician NFs are not expected to suffer from the same bias as the existing ones (i.e. the underestimation of the toxicity references), but that they would need to be further tested in subsequent case studies to confirm it, and until then, used with care in comparative case studies.

4.3.3 Impacts of carbon compensation in water scarcity

Being the Galician CF and NFs the main outcomes of this document, not only their results (and the methodological approaches followed to obtain them) could be refined.

A simple procedure to choose the best possible location for carbon compensation projects has also been proposed in this thesis. This is seen as a promising methodology to locate afforestation projects.

Chapter 5: Conclusions

As a result of the work carried out within the development of this thesis, several conclusions can be drawn, split here between general (referring to the Galician CF and NFs) and specific ones (referring to the individual LCA studies of products).

5.1. General conclusions

This thesis successfully applied a procedure based on type B territorial LCA to calculate the normalisation factors of all Galician consumption and production activities.

To the best of our knowledge, this is the first application of this approach to obtain normalisation factors, and the Galician ones are the first subnational references available.

These Galician NFs, calculated following a life cycle approach, are expected to be more consistent with the reference systems used in LCA studies of individual products.

An *intra* double counting solving procedure has been proposed to allow applying territorial LCA to regions in which production activities are linked to each other, based on IO tables.

When calculating both the Galician carbon footprint and its normalisation factors, the main hotspots were identified:

- Within consumption, housing and food consumption.
- Within production, electricity generation and food manufacturing.

Some measures for the lowering of these impacts have been proposed, i.e. the use of cleaner energy sources both in housing and in the regional electricity mix, the reduction of the consumption of livestock based products and of the emissions from their production, and the use of collective means of transport.

Special attention has been paid to the carbon footprint results, for which different calculation methodologies were compared, seeking both to improve their reliability and to simplify the calculation procedures. An approach based on the Galician IO matrix (MIOGAL) was suggested to obtaining reliable, quick CF results for Galicia or other regions having IO tables.

As already acknowledged throughout this document, even when several improvements have been implemented on the territorial LCA approach, there is always room for the continual improvement concept on the search of more reliable results or more simple calculation procedures. The substitution of the USEIO based inventories by MRIO data (ideally Galician based) could largely improve the reliability of the results, but some other improvements could be more easily carried out, such as the updating and refining of the PA based inventories.

5.2. Specific conclusions

Apart from the findings linked to the main outcomes of this thesis (i.e. the Galician CF and NFs) some other conclusions can be drawn from the work included here:

The water footprint indicator can be used to choose among locations for afforestation projects. This was stated through a very simple approach, which should be better refined to allow for a more reliable calculation of evapotranspiration values.

A study evaluating the updated carbon and water footprints of Galician milk production has been carried out, and it was found that GHG emissions from the livestock sector could be significantly reduced by improving the cows' diet (which would also have a positive influence in consumer health). Thus, an alternative to the usual ways forward for the lowering of the livestock GHG impacts has been proposed.

A procedure to account for different load factors in Ecoinvent transport inventories has been proposed, which can be used to model transport stages when the truckload is known and different from the average one.

Refined emission factors for nitrous oxide in tropical climates, adapted to several soil textures have also been proposed, which could be used instead of the default IPCC factors, suitable for warm climates only.

Section 6: References

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