Downscaling material flow analysis: The case of the cereal supply chain in France

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Abstract

The spatial reconstruction of the production, trade, transformation and consumption flows of a specific material, can become an important decision-help tool for improving resource management and for studying environmental pressures from the producer's to the consumer's viewpoint. One of the obstacles preventing its actual use in the decision-making process is that building such studies at various geographical scales proves to be costly both in time and manpower. In this article, we propose a semi-automatic methodology to overcome this issue: we describe our multi-scalar model and its data-reconciliation component and apply it to cereals flows. Namely, using official databases (Insee, Agreste, FranceAgriMer, SitraM) as well as corporate sources, we reconstructed the supply chain flows of the 22 French regions as well as the flows of four nested territories: France, the Rhône-Alpes région, the Isère département and the territory of the SCOT of Grenoble. We display the results using Sankey diagrams and discuss the intervals of confidence of the model's outputs. We conclude on the perspectives of coupling this model with economic, social and environmental aspects that would provide key information to decision-makers.

Keywords: material flow analysis, supply chain, downscaling, data reconciliation, cereals, France

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1. Introduction

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2003). Depending on the pursued objective (e.g. detoxification, dematerialization etc.), this framework has been implemented for various scopes de facto creating a family of methodologies, ranging from Substance Flow Analysis to Economy-Wide Material Flow Accounting (Bringezu and Moriguchi, 2002). In this paper, we are interested in mapping the flow of specific resources throughout the economy, both from a spatial and a processing point of views; i.e., we aim to trace the associated flows from the extraction of raw materials to the processing, trade and consumption of the derived products based on the resource under consideration. These studies are known as MFA on the level of goods, as defined by Baccini and Brunner (2012)[1]. In their original work, Billen et al. (1983) conducted such MFA on 6 supply chains at the scale of Belgium (iron, glass, plastic, lead, wood and paper, and food products). Since then, MFA has been mostly applied to metals[2] (Ciacci et al., 2013), (Eckelman and Daigo, 2008), (Liu and Müller, 2013), (Dahlström and Ekins, 2006), (Bonnin et al., 2012) to cite only a few. Some studies were also undertaken on construction materials (Smith et al., 2003) and wood (Hashimoto and Moriguchi, 2004), (Binder et al., 2004), (Cheng et al., 2010). Regarding food products, few studies actually quantified flows between the production, transformation and consumption stages (Blezat-Consulting, 2010), rather focusing on the supply of a product unit (Narayanaswamy et al., 2003), (Mintcheva, 2005), (Virtanen et al., 2011), or on regional nitrogen flows (Billen et al., 2009).

Binder et al. (2009) raised the important issue of the practical usefulness of large-scale MFA studies for policy-making. Three main obstacles were identified in comparison with MFA at the scale of an industrial unit: *"(i) the numbers of stakeholders involved increases [...] and it becomes unclear who is responsible for taking action; (ii) the uncertainty of the data increases; and (iii) the goals [...] are not always clearly defined"*. In order to bridge the gap between research findings and policy-making, many authors have rightly argued that MFA should be coupled with social, economic or/and environmental models (Binder, 2007). This kind of coupling was for instance successfully implemented by Rochat

[1] Two kind of materials are distinguished: substances, that is *any chemical element or compound composed of uniform units*, and goods, that is *economic entities of matter with a positive or negative economic value [...] made up of one or several substances* (Brunner and Rechberger, 2003).

[2] Many investigations dedicated to metals life-cycle flows are linked to the Stocks and Flows (STAF) project at Yale university.

et al. (2013) who combined MFA, Life Cycle Assessment (LCA) and multi-scenarios, multi-criteria, multi-stakeholders analysis to address the issue of PET plastic management in Columbia. One could also refer to the study carried out by Bouman et al. (2000) who used SFA, LCA and partial equilibrium models to evaluate industrial systems and compare pollution management scenarios. Coupling MFA with a social model aims at better understanding the behaviors of stakeholders and the interactions between them in order to study how to improve resource management. For instance, Binder et al. (2004) used a multi-agent model to study the management of regional wood flows in Switzerland. As mentioned by Kytzia et al. (2004), the coupling of MFA with an economic model can be performed to study economic consequences of environmental policy, or on the contrary, to study the effectiveness of economic tools to tackle environmental issues. Finally, the coupling with an environmental model, for example with LCA, makes it possible to build environmental accounts (such as footprints) from the producer's and from the consumer's perspective. As underlined by many authors (e.g., Peters and Hertwich 2006; Skelton et al. 2011), these points of view are both complementary and paramount for policy-making. The producer's point of view informs on environmental pressures that occur on a territory: a variety of measures (incentives, regulations, information...) can be taken to address these pressures. The consumer's point of view informs on the responsibility of the consumer for environmental burdens occurring locally or far away (end products purchased by final consumers trigger global supply chains and thus it can be argued that consumers bear the subsequent environmental pressures).

The present paper is the first step of a project aiming at analyzing local supply chains from an economic, social and environmental perspective for decision-aiding. In particular we aim at analyzing environmental pressures along supply chains, i.e. from the producer's to the consumer's viewpoint. The paper has two main objectives. The first one is to assess the feasibility of downscaling a national MFA to simultaneously obtain MFAs on every subterritory the country is composed of (e.g. every regions). This makes the study more time-efficient while also ensuring the comparability of the data and the consistency of aggregated results (the regional data will sum up to the national data). These results can then serve as a basis for discussion and refinements with local stakeholders. The second goal is to undertake a multi-scale MFA. We strongly believe that multi-scale analysis is a powerful decision-help tool given social-environmental issues are unlikely to be resolved at any single administrative level. Such a perspective has already been adopted in France in the case of Paris and its region where economy-wide MFAs were produced on three different geographical scales (from the city to the région level; Barles (2009)). Here, we undertake studies at the national, regional, departemental and SCOT[3] scales.

In order to illustrate the interest of the tool we have developed, we have chosen to apply it to a basic class of commodities, i.e., cereals. This choice is motivated by the following considerations:

- At the world's scale, but more generally at any scale, the supply of cereals and cereals products is strategic given their direct and indirect (through meat consumption) role in human diets and their increasing use for other purposes (e.g. bioethanol),
- Cereals are, in terms of weight of production, the most important agricultural good in France; the supply chain is represented all over the territory and, at the same time, a strong heterogeneity can be observed between regions,
- The supply chain is well structured making it easier to model and collect the necessary data.
- Finally, it is possible to account for most end-products derived from cereals with a limited set of descriptive product categories, bread being the most obvious one in the case of France.

The paper is organized as followed: the first section depicts the methodological framework and the sources and hypotheses used in the modelisation phase, we present and discuss the results in the second section before concluding on the perspectives for further research in the field of MFA.

2. Materials and methods

2.1. Methodological framework

In order to semi-automatically produce MFAs at subnational scales, we start by building a consistent MFA at the country level. For this purpose, we use on the one hand a supply and use tables (SUTs) framework as a way to present and organize the data, and on the other hand a constraint optimization algorithm aiming at reconciling inconsistent data. We underline here that while we use a typical Input-Output framework, we don't go into any IOA (e.g. computation of the Leontief matrix)[4].

It is worth noting our resource-specific MFA based on SUTs is close to the concept of Material System Analysis (MSA) introduced by Moll et al. (2005) on the case of European iron and steel flows,

[3] Schéma de cohérence territoriale: the SCOT is an urban-planning document dedicated to a group of towns or urban areas.

[4] French IO tables indeed come into a too aggregated form to reach the level of detail we are interested in here.

and taken up by OECD (2008). However, while MSA is considering all material inputs and outputs along the supply chain (i.e. life-cycle-wide), we only focus at this step on one good: cereals[5].

2.1.1. Supply and use tables

Handling a large quantity of data is a major difficulty in MFA and calls for a proper way of organizing the information. SUTs appear to be the most convenient framework to achieve this goal. They comprise a Supply table, which indicates the origin of the goods (either sector-wise or geographically) and a Use table, which indicates the destination of the goods.

[5]The study of specific material/environmental flows associated with it will be tackled in a next step as described in the introduction.

	industry 1 .. industry m	imports
product 1 .. product n	V_{ij} (n,m)	I_i (n,1)

Table 1: Supply table and matrices notations. The numbers in brackets indicate the dimensions of the matrices.

	industry 1 .. industry m	exports	consumption
product 1 .. product n	U_{ij} (n,m)	E_i (n,1)	C_i (n,1)

Table 2: Use table and matrices notations.

As shown above, the supply table comprises the supply matrix V and the imports vector I whereas the use table comprises the use matrix U, the exports vector E and the (final) consumption vector C. For instance U_{ij} refers to the quantity of product i that is used by sector j and C_i refers to the quantity of product i that is consumed by end-users on the territory. The constraints linking these elements are discussed in section 2.1.3.

Using SUTs implies to make a list of the goods deriving from the primary resource under study, i.e. the primary material itself, semi-products, by-products and end-products. Finding the appropriate level of details for both products and industries is an iterative process between looking for sources of information and trying to fill the tables. With a small number of highly aggregated product categories, the study isn't likely to provide useful information and with a very detailed list of products and industries, filling the data, especially at local scales, won't be feasible. A good knowledge of existing classifications in the national statistical system, for instance economic sectors, products or traded commodities classifications, is also required because correspondences between them will be needed. We used the most precise level of classification of economic sectors available in France for most of the sectors in the study: the NAF 2008 classification (732 sub-classes). For some important products such as bioethanol, this classification was however not precise enough. In those cases, we created our own sectors, knowing information on factories location was available from the cereals' supply chain federation. This initial step of supply-chain structure analysis is the most time-consuming and cannot be automatized. In fact, it consists in building a model of the supply chain: a too coarse model will not make sense while a too detailed one will be intractable. The final version of our study includes 19 products and 18 sectors (displayed in figure 11 in Supplementary Material section A).

2.1.2. Boundaries of the study, units and allocation choices

We used a typology proposed by Nakamura and Kondo (2009) to define the scope of the study. Inputs from sector a to sector b can take three different forms: primary material inputs, that will be physically incorporated in the production of sector b (e.g. wheat for flour production), material ancillary inputs, that are necessary for production of sector b but not part of it (e.g. machines), and finally flows of services. For this MFA on cereals we track the flows from product to product until cereal grains are no more physically present in the output of the process. Thus, we go for instance from wheat to flour and to bread and biscuits while we stop the study at animal feed without analyzing the embodied cereals in the meat finally consumed (which would be virtual allocation and not a physical flow of cereals).

Like other MFA studies on the level of goods, we converted all flows to a common unit[6]. Here, flows are expressed in cereals grains equivalent (c.g.e.). The c.g.e. weight equals the real weight when the product under consideration is entirely made out of cereals (e.g. flour), otherwise (e.g. bread, beer...), it represents the weight of the cereal content of the product.

To sum things up, our SUTs framework distinguishes itself from SUTs traditionally used in national accounts by the finer-grained description of the products and industries categories, by the fact that it focuses on a single supply chain and by the choice of the unit.

2.1.3. Data reconciliation

The principle of mass conservation provides a few constraints on the SUTs. When the data comes from distinct sources, these constraints are of course very unlikely to be fulfilled. Making the original data fit the constraints is commonly referred to as the data reconciliation process. The constraints are discussed below.

We first apply the law of mass conservation on each product: the amount of product that was used during the considered time period by transforming industries, exports and final consumption, had to be supplied by local industries or by imports *(constraint 1)*. The corresponding equation is:

$$\sum_j \hat{V}_{ij} + \hat{I}_i = \sum_j \hat{U}_{ij} + \hat{E}_i + \hat{C}_i \qquad i = 1..n \tag{1}$$

We use hats above letters to refer to the data resulting from the reconciliation process (original data are represented without a hat). In the general case, equation 1 should contain additional terms to account for initial and final stocks (or alternatively one term of stock variation). We however go around this issue as explained in section 2.2.4. Moreover, losses are treated as a sector (without outputs) in matrices U and V.

We apply a similar principle of conservation to every transforming industrial sector *(constraint 2)*: the sum of a sector's inputs is equal to the sum of its outputs:

$$\sum_i \hat{V}_{ij} = \sum_i \hat{U}_{ij} \qquad j = 1..m \quad \text{and j is a transforming sector} \tag{2}$$

[6]For instance, Binder et al. (2004) and Cheng et al. (2010) convert all flows of wood-related products into their equivalent in cubic meters of round-wood.

A sector producing raw materials is not concerned by this constraint because it only has outputs. We moreover implement a few process constraints to verify classical technical conversion factors between products *(constraint 3)*. These equations link one or more inputs of a transforming sector with one or more of its outputs. For instance the yield of conversion of wheat grains into flour translates into the following constraint for the milling sector : $S_{flour,mills} = 0.77 * U_{wheat,mills}$. We present those equations in table 8 in section A of Supplementary Material. Finally, we want all terms to remain positive *(constraint 4)* and most of the terms to remain null *(constraint 5)* because of the supply chain modelisation choices (for instance the primary production sector cannot produce transformed products).

Our goal is to minimize the discrepancy between original data and estimated/final data while respecting the constraints. This problem can be expressed in many ways depending on the expression of the distance between original and final data. We choose here one of the simplest, a weighted least square problem under constraints:

$$\begin{aligned} \min \quad & \Big(\sum_i \sum_j \frac{(\hat{V}_{ij} - V_{ij})^2}{\sigma^2_{Vij}} + \sum_i \sum_j \frac{(\hat{U}_{ij} - U_{ij})^2}{\sigma^2_{Uij}} + \sum_i \frac{(\hat{I}_i - I_i)^2}{\sigma^2_{Ii}} + \sum_i \frac{(\hat{E}_i - E_i)^2}{\sigma^2_{Ei}} \\ & \quad + \sum_i \frac{(\hat{C}_i - C_i)^2}{\sigma^2_{Ci}} \Big) \\ & \text{subject to the set of constraints 1 to 5} \end{aligned} \tag{3}$$

In equation 3, σ refers to the assumed standard deviation of the data. They make it possible to treat data sources differently depending on the assumed (or possibly measured, or constrained) uncertainties on the data. The chosen weights are discussed later in the paper.

2.1.4. Downscaling technique

From an administrative point of view, metropolitan France is currently divided in 22 administrative régions. Each région is further subdivided into départements (96 in total), the next and last administrative authority being towns and cities (about 36000 in total). The lack of data at local scale is problematic. The smaller the scale, the less the availability of the data. For this reason, one can try to estimate the missing data using other existing variables along with data available at a larger scale, by defining appropriate proxies.

The general proxy expression of the estimation of local data would be:

$$Y^{n+1} = f(Y^n, X_1^{n+1}, \, .. \, , X_k^{n+1}) \tag{4}$$

Here the exponents refer to the geographical level of the data (for instance, if n represents the country level, $n+1$ represents the regional level). f is the model linking the quantity of interest at level n, Y^n (known), and k explanatory variables available at level $n+1$, X_j^{n+1}, to the quantity of interest at level $n+1$ that we are looking for: Y^{n+1}.

The possibilities of testing complex proxy models are of course very limited by the scarcity of the information. Researchers who faced the lack of data in their local MFA studies actually used a single proxy (or explanatory variable) to estimate missing data (Barles, 2009) (Kovanda et al., 2009) (Niza et al., 2009). This is usually based on reasonable hypotheses such as "consumption is almost proportional to the population". We applied the same approach here and conducted linear regression tests whenever the sample existed and was of sufficient size[7]. We studied the possibility of having a multiple explanatory variables model but concluded it wasn't robust enough given the limited size of the geographic sample (Smaranda, 2013). Moreover, we found that the R^2 index, which represents the proportion of the variability of the sample that has been explained by the model, was high enough in the case of a simple one-explanatory-variable-linear model to consider it satisfactory. Results are presented in Table 4. For instance, if we want to estimate the regional use of wheat by the milling industry in region i, $U^{r_i}_{wheat,mills}$, with the number of employees working in this sector E_{mills}, equation 4 becomes:

$$U^{r_i}_{wheat,mills} \;=\; U^{fr}_{wheat,mills} \;*\; E^{r_i}_{mills} \;/\; E^{fr}_{mills} \tag{5}$$

Once enough direct data or proxies have been gathered, it is possible to fill the SUTs. New columns are added to consider inter-regional trade of good. By construction, the imports of product i to region a from region b, $Ir_i^{a,b}$, are equal to the exports of product i from region b to region a, $Er_i^{b,a}$, so we only use the Ir variable (matrix) in the program. We then apply the same data reconciliation process as the one described above. An additional constraint however needs to be implemented: one wants to ensure the coherence of the results regarding aggregation and disaggregation. The regional data must sum up to the national total. With the same notations as above for the exponents, the general expression of the aggregation constraint *(constraint 6)* is:

$$\sum_i \hat{X}^{n+1,\, i} = \hat{X}^n \qquad \text{where } \hat{X} \text{ represent matrix } \hat{V}, \hat{U}, \hat{I}, \hat{E} \text{ or } \hat{C} \tag{6}$$

[7] The fact that the sample size is small (96 individuals at best) has to be balanced by the fact that it is exhaustive.

In equation 6, I and E refer to international imports and exports only: there is no aggregation constraint on inter-regional trade.

There exists no trade database at subnational scales that perfectly matches our products classification. Therefore, a few traded categories are more aggregated than our own categories. For instance the *wheat* category in the transport database includes both our *common wheat* and *durum wheat* categories. Table 16 in section B of Supplementary Material shows the full correspondence and section B depicts the changes that had to be made to take this limitation into account.

Finally, no trade data is available below the level of the département. Therefore, at this scale, we only compute production and consumption (intermediate and final) flows, using the usual proxis and then apply the resource equals use constraint on each product to determine the amount of net imports (or net exports). Thus, we no longer use any optimization or data reconciliation process below the scale of the département.

2.2. Data sources and hypotheses

Figure 11 in Supplementary Material section A shows the classifications used in this study for product and sector categories together with the chosen modelisation of the supply chain: it indicates for instance that the starch industry uses common wheat and maïze and supplies starch and residues. In order to fill the SUTs, the information we are looking for fall into different categories: primary production, intermediate consumption, stocks, trade, livestock consumption and final consumption. As mentioned in the previous section, we use direct data when it exists and proxy data otherwise. Each type of information is discussed below in relationship to table 3 that summarizes the sources and table 4 that presents the chosen proxies. The question of data uncertainties is discussed in the last paragraph of the section.

Item	Source	Smallest scale available
Production of each type of cereals (common wheat, durum wheat, maïze, barley...)	Statistique Agricole Annuelle (Agreste): `http://acces.agriculture.gouv.fr/disar/faces/`	département (better resolution can be purchased as long as it does not go against statistical secret)
Production of intermediate products (flour, bread, biscuits, starch, semolina, pasta, malt, beer...)	Bilans d'approvisionnement (Agreste): `http://agreste.agriculture.gouv.fr/enquetes/bilans-d-approvisionnement/cereales-riz-pomme-de-terre/`, cereals' inter-profession `http://asset.keepeek.com/permalinks/domain39/2013/06/04/927-B18-Des_chiffres_et_des_cereales__edition_2012-2013_-_page_a_page.pdf`	country
Animal feed (for cattle, poultry and pigs)	Bilans d'approvisionnement (Agreste)	country
	Inputs used by the animal feed industry (Agreste)	most of the régions
International trade of raw materials and transformed products	Bilans d'approvisionnement (Agreste)	country
	SitraM database (based on French customs' data)	département of origin/destination - country of origin/destination
National road freight	SitraM database (based on the TRM survey)	département of origin/destination - département of origin/destination
National railroad freight	SitraM database (based on reports from SNCF - available until 2006)	région of origin/destination - région of origin/destination
National river freight	SitraM database (based on reports from VNF)	département of origin/destination - département of origin/destination
Cereals' consumption patterns	Babayou et al. (1996)	régions

Table 3: Available sources for data in weight unit (all recent years are available when applicable)

Item	Proxy and source	Sample size	R^2 (and p-value)	Used for scales...
Cereals production	Arable land (code 211) - CORINE Land Cover	96	0.95 (2e-62)	< département
Total livestock feed	Livestock at subnational scales - Statistique Agricole Annuelle (Agreste) for régions and départements, Recensement Général Agricole 2000 (Agreste) for town	see the lifestock feed section		< country
Flour production	Employment (sector 10.61A)	12	0.75 (2e-4)	< country
Production of semolina	Number of factories	not tested		< country
Production of cornmeal	Number of factories	not tested		< country
Rice transformation	Number of factories	not tested		< country
Production of canned corn	Number of factories	not tested		< country
Starch production	Employment (sector 10.62Z)	3	0.96 (0.13)	< country
Industrial bread production	Employment (sector 10.71A)	not tested		< country
Production of bread in supermarkets	Employment (sector 47.11F)	not tested		< country
Craft bread production	Employment (sector 10.71C)	not tested		< country
Biscuits production	Employment (sector 10.72Z)	not tested		< country
Pasta production	Employment (sector 10.73Z)	not tested		< country
Livestock compound feed production	Employment (sector 10.91Z)	18	0.96 (1e-12)	< région
Malt production	Employment (sector 11.06Z)	3	0.99 (0.06)	< country
Beer production	Employment (sector 11.05Z)	not tested		< country
Bioethanol production	Number of factories	not tested		< country
Final consumption	Population coupled with consumption pattern - Population census (Insee), Babayou et al. (1996)	not tested		< country

Table 4: Chosen proxies. R^2 can be interpreted as the fraction of the sample's variability that is explained by the linear model. The p-values (in brackets) represent the probability of obtaining a similar or better R^2 value if the null hypothesis is true (i.e. if there is no relationship between the explanatory and response variables). One usually assumes the null hypothesis is false when the p-value is below 0.05. Here, we can validate the explanatory models for cereals, flour and livestock feed production whereas the samples are too small to validate the starch and malt production models. Insee's CLAP database is used to get the number of employees; number and location of factories come from the yearly report of the *Passion Céréales* association (inter-profession). Hypotheses were not tested when no data was found at the regional scale.

2.2.1. Primary production

Detailed data on cereals production is published in the annual agricultural statitics available down to the level of the département. We therefore used a land-use proxy (see table 4) to estimate the production of cereals at the scale of a group a cities.

2.2.2. Intermediate consumption

The annual report of the French inter-profession of cereals (Passion-Céréales, 2013) provides information on the quantities used and produced by different industries in the supply chain. Based on this data, we established conversion factors between products (table 8 in Supplementary Material section A), that are used to constrain the problem (see section 2.1.3). When the data couldn't be found in specific regional reports, which is the general case, we estimated the subnational intermediate consumptions using the downscaling technique presented in the previous section and the proxies in table 4.

2.2.3. Livestock feed

Regional consumption of cereals for livestock feed are not directly known, mainly because the cereals are distributed in various forms: mostly self-consumption at the farm and consumption of industrial compound products, and marginally grains bought by the farmer. We therefore designed a model to estimate these consumptions. Figure 1 presents the general principle of the model: we estimate the local livestock consumption of cereals based on the data on livestock and slaughter and on the nutritional needs of the animals. Data source for livestock, slaughter and production figures are shown in table 3. We estimated the nutritional needs based on zootechny guidebooks (see table 3) and then scaled them in order to make them consistent with the total cereals animal consumption provided in the national accounts of the ministry of agriculture. Table 10 in Supplementary Material section A shows the modeled distribution of cereals feed among the main categories of animals before and after this adjustment process: the scaling ratio obtained is moderate (1.13), indicating that the model is probably robust. In order to derive this table, we distinguished about 20 different types of animals and products. Tables 11, 12 and 13 in Supplementary Material section A show the original feed intakes per type of animal or product. Care was taken in order to avoid double-counting: either the lifecycle or the annual approach was used for each product. For instance, we use the lifecycle approach for pigs (meaning we multiply the number of pigs slaughtered during one year by the cereals intake of one pig during its lifespan) and the annual approach for nursing cows (meaning we multiply the livestock at the end of the year by the per capita annual feed intake). Once local cereal feed consumption is estimated, we split it between compound feed and raw feed thanks to information and hypotheses on the animal feed industry (tables 3 and 4).

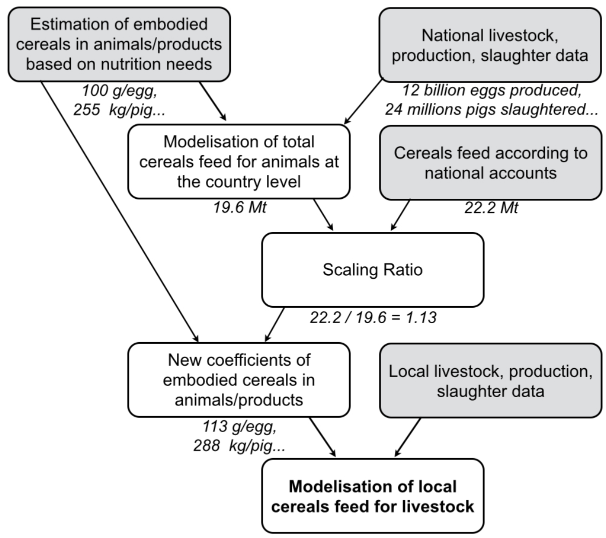

Figure 1: Principles of the livestock feed model. Input data is shown in grey.

2.2.4. *Stocks*

Information about stock is partial, notably because of confidentiality issues. Averaging the figures over several years solves this issue since the variations of stock tend to compensate one year after another. For instance, table 9 in Supplementary Material section A shows that stock variation explains up to 12% of the national apparent consumption in 2003 whereas this number falls to -0.6% over the period average. In this work we therefore study the period 2001-2009.

2.2.5. *Trade*

As shown in table 3, for the national MFA, we use the imports and exports data of the ministry of agriculture, providing information with detailed product categories directly in weight of grain equivalent. For MFAs at subnational scales, we use the SitraM database, maintained by the French ministry of ecology. We underline 3 main difficulties with this data :

1. We had to design a correspondence table between the transport statistics classification and our own product classification : table 16 in Supplementary Material section A.
2. Assumptions had to be made regarding the national trade by railway since the classification is not as detailed as for the other modes of transport: we assume that cereals represent 75% of the "Agricultural products and living animals" category. This is the proportion found for international export by railroad in 2005.
3. Theoretically, there is a compatibility issue between data from the customs (international trade) which provides the first origin and final destination of a product and the national data which provides the last loading or unloading of the merchandise. This issue can lead to double counting for regional imports and/or for exports[8]. We partially solved the problem by redistributing the international trade by sea using the market shares of French harbors for cereals exports. This means in particular that sea exports of regions without any harbors were entirely reallocated to regions with harbors. We were not able to do the same for road, river or railway transport. Still, this operation is significant since more than half the French exports of cereals are made by sea: on average, between 2001 and 2009, France exported about 14 Mt of cereals by sea, 6 Mt by road, 5 Mt by river, and 1,5 Mt by railroad. Table 14 in Supplementary Material section A shows the impact of this operation on the total international exports of every regions.

2.2.6. *Final consumption*

Final consumption of cereal products occurs in two forms: food products (bread, biscuits, pasta...) and industrial products (bioethanol and many products derived from starch). In France, local consumption patterns are not precisely documented, at least not precisely enough to be used in this study. For most of the products, we considered the per capita consumption to be equal all over France. Regarding bread, we used a study depicting the diversity of food consumption patterns in France in the mid 1990's that presents statistical information on the gap between regional and average consumption of bread per household (Babayou et al., 1996). This consumption estimation is not built as an apparent consumption (resulting from the difference between production, stock variation and trade) but on direct households surveys. Table 15 (supplementary material) presents the adopted regional adjustment factors for per

[8]For instance, French wheat loaded in the Centre région, transported by road to the Rouen harbor and then exported by sea to Algeria will be counted in the customs statistics as *from the Centre région to Algeria* and in the national transport statistics as *from the Centre région to Rouen*, leading to a double-counting of exports of the Centre région.

capita bread consumption, reconstructed from this report. For subregional scales, no data was found in the report. Following the conclusions of Babayou et al. (1996), that the urban vs. rural and north vs. south typology was the most suited to explain the variability in the bread consumption patterns (rather than regional cultural differences for instance), we estimated the gap between local and average consumptions based on this typology. Table 5 shows the corresponding adjustment factors.

	Urban	Rural
North	-10%	+21%
South	-7%	+25%

Table 5: Per capita bread consumption variability among different categories of towns in the mid 1990's in France (Babayou et al., 1996). The table makes the distinction between cites in the north and in the south of France and between urban and rural cities (cities with less than 2000 inhabitants are considered rural). According to these authors, this typology is the most suited to explain the differences between bread consumption patterns in France.

According to the national MFA, bread accounts for about 40% of the consumption of cereals for food purposes, and for one third of the total consumption of cereals. This adjustment on local bread consumption is therefore significant.

2.2.7. Data uncertainty

Uncertainties on input data

Laner et al. (2014) review existing literature regarding uncertainty handling in MFA and provide recommendations relatively to the goals of each study. Our case study typically falls in the category of descriptive MFA as they describe it and we use an approach similar to the one implemented in software STAN (Cencic and Rechberger, 2008): input data are expressed by a mean and a standard deviation reflecting the level of confidence in the data. As we mentioned in section 2.1.3, the weighted least squares optimization leads to higher alteration (difference between output and input data) of variables with higher uncertainties. Since none of the sources used provides detailed information on data uncertainty, this step is based on assumptions and on educated guesses. Following Danius (2002), we treat data differently depending on its origin. Below, we list the different origins from the ones we trust the most to the ones we trust the less:

1. official statistics at local, regional or national scale, based on cross-checking of surveys (some of which are exhaustive) : e.g. agricultural production, employment...
2. statistics based on declarations (and punctual control): e.g. customs, reporting from the supply chains' federations...
3. modelised local data, based on downscaling,
4. extrapolation of statistical surveys on sub-populations

The last one typically applies to road freight statistics which are based on a survey[9]. The estimation of total road freight in the country (all goods combined) is quite accurate (less than 1% of error according to the calculation of the statistical office (SOeS, 2012)), however the extrapolation on subpopulations, meaning on specific goods in specific regions, can be deteriorated a lot because of the small size of the sample. Collaboration with the statistical office is in progress in order to estimate the intervals of confidence on these subpopulations. Generally we consider that small flows have a larger relative

[9]This survey is mandatory for all European Union members.

error than large ones for data extracted from the same source, but we prevent null flows from having a vanishing standard deviation (this would be unrealistic).

Although the attribution of uncertainty weights is based on objective elements such as the source of the data, this part of the process is not the most robust and the model would benefit from a sensitivity analysis that would show the impact of a change for each input variable. This was however too demanding to accomplish in this paper (this would require to rewrite our Matlab code in a more efficient language such as C for the simulations for the computational time to remain within reasonable bounds).

Uncertainties on output data

Using common terminology in statistics, we can describe our problem as follow: if we call a supply-use table with uncertainties on each parameter a supply-use table distribution (STUD), then our goal is to obtain a posterior STUD from our prior STUD. Given the number of constraints we know our result is of much lower dimension than the number of variables and a direct sampling of the posterior STUD is then possible by Monte-Carlo simulations. The intervals of confidence of output variables are thus inferred from theses simulations. Numerous input datasets are randomly generated knowing the standard deviation of input data, and assuming a Gaussian distribution (although this is not a requirement). After a while, typically in our case, a few tens of simulations, the process reaches convergence. The confidence intervals represented on the diagrams correspond to two standard deviations (95% of possible values if the actual distributions are indeed gaussian). We analyze the results in section 3.

2.3. Software integration

We wrote a program to properly integrate our databases, the original SUTs, the optimization and Monte-Carlo processes, and the visualization of results. As table 6 illustrates, it made it possible to implement a model with a large quantity of variables, simultaneously computing all sub-entities of a given territory. Figure 2 presents the software background on the study in relation to figure 3 which shows the manual and automatic steps conducted to produce regional results.

Geographical scope	Scale	Number of MFAs (territories) computed	Number of output variables (of which are forced equal to zero)	Execution time
France	France	1	741 (637)	about 10 secs
France	Regions	22	25498 (14428)	about 40 min
Rhône-Alpes	Departements	8	13832 (5582)	about 10 min

Table 6: Characteristics of each run of the model (one line corresponds to one run). We first obtain the national MFA, then downscale it to obtain results in every region, and finally downscale the Rhône-Alpes results in every departement of the region. The 741 variables of the first run are decomposed as follow: 361 variables for the supply table (19 products * 18 sectors + 19 variables for international imports) and 380 variables for the use table (19 products * 18 sectors + 19 variables for international exports + 19 variables for consumption). The 25498 variables of the second (regional) simulation are decomposed as follow: 16302 for the "basic" supply and use tables (22 regions * 741 variables), 9196 variables for inter-regional trade. We use sparse matrices for the computation as many variables are null (see constraint 5 in section 2.1.3)

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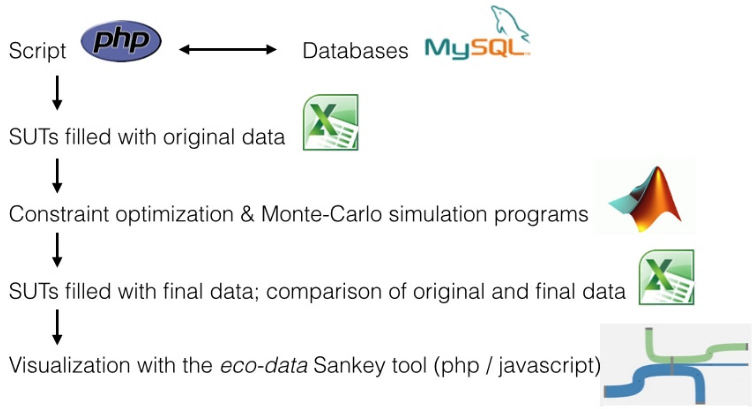

Figure 2: The chain of computation and integration between softwares.

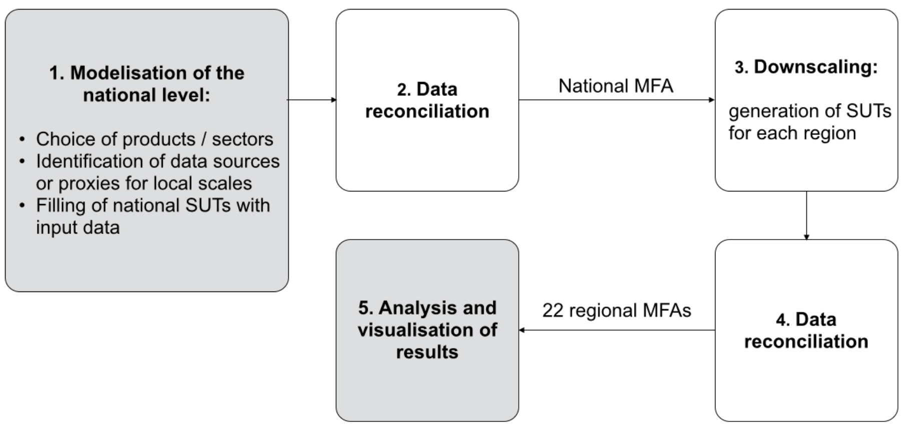

Figure 3: Steps taken to produce regional MFAs. Automatized parts are shown in white. SUTs: supply-use tables.

3. Results and discussion

We use Sankey diagrams to display our results[10]. They have long been used in flow studies and are very efficient in wrapping a large quantity of information (Schmidt, 2008). We use the following convention: flows circulating inside the territory are represented by horizontal lines while flows entering or leaving it are represented by vertical lines. Although the core of the paper only shows results under this form, all input and ouput datasets are available by request to the authors.

3.1. Results for France and French regions

We split the national results into two diagrams in order to make them more readable. Figure 4 shows the production, imports and exports of cereals as well as the flows related to livestock consumption (raw or compound feed). With a yearly average of 34 Mt of grains produced, common wheat is the most commonly grown cereal in France (53% of the total cereal production) before corn (23%) and barley (16%). This production of about 65 Mt is mainly dedicated to exports (about 27 Mt or 42%). Although the information doesn't appear on the diagram, about 2/3 of these exports go to European countries and 1/4 to African and middle-east countries, according to customs data. The rest of the production goes to livestock feed (about 22 Mt or 34% evenly divided between raw and compound feed) and other interior uses (about 16 Mt or 25%). Imports are almost negligible (less than 1 Mt)[11]. Finally cereals grouped in the *other cereals* category are only used for exports and for livestock, except for rice.

[10] There is a clear link between SUTs and their representation in Sankey diagrams. Products, and activities (industries, imports, exports and consumption) are the nodes of the diagram. The values in the supply table are represented by links going from activity nodes to product nodes and the values in the use table are represented by links going from product nodes to activity nodes. For the purpose of this study we developped a Sankey software that can be used on www.eco-data.fr/tools/sankey/start.php

[11] It can be noted that French livestock depends a lot on imports of soycakes (nearly 5 Mt are imported each year, mostly from Brazil and Argentina) but this is not in the scope of the cereals study.

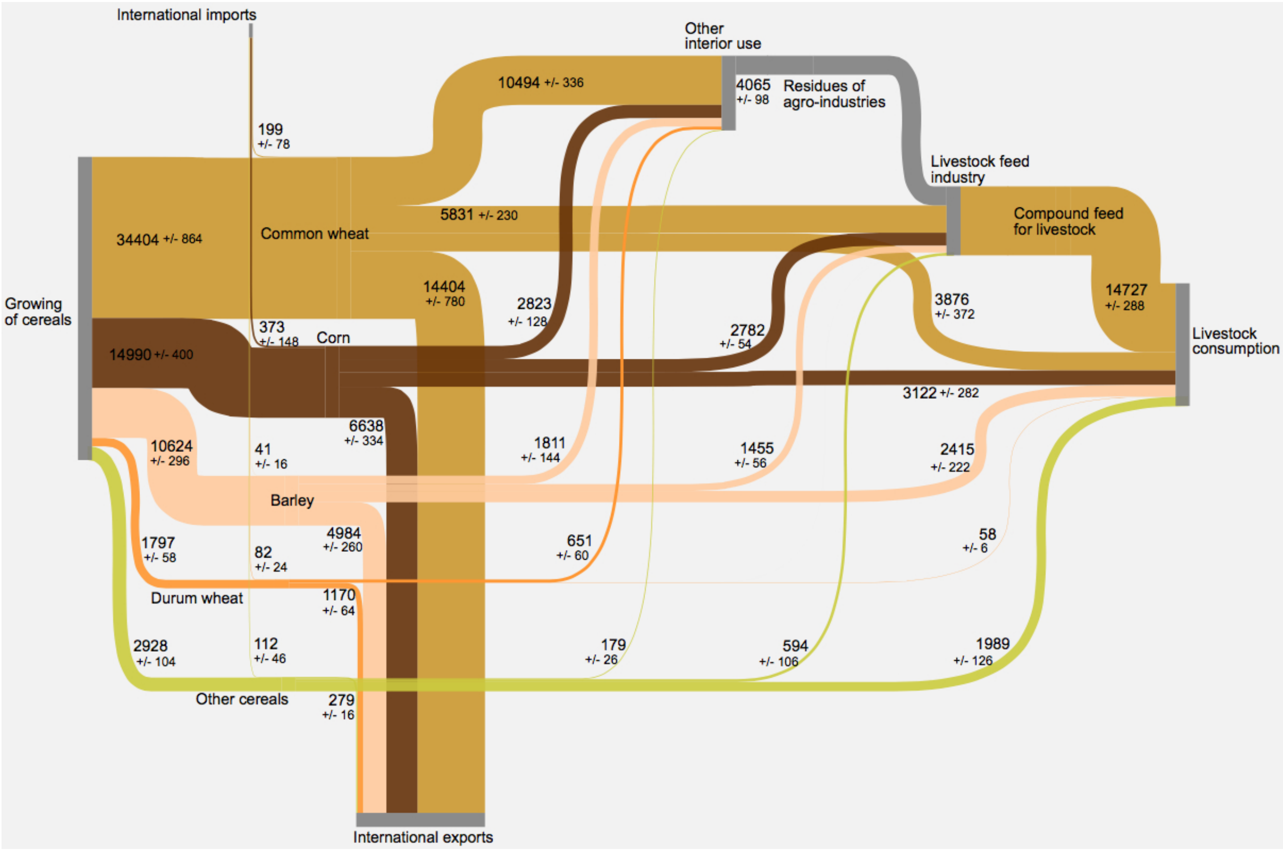

Figure 4: Cereals MFA at the scale of France: international trade and animal feed. Results are shown in kilotonnes for an average year over the period 2001-2009.

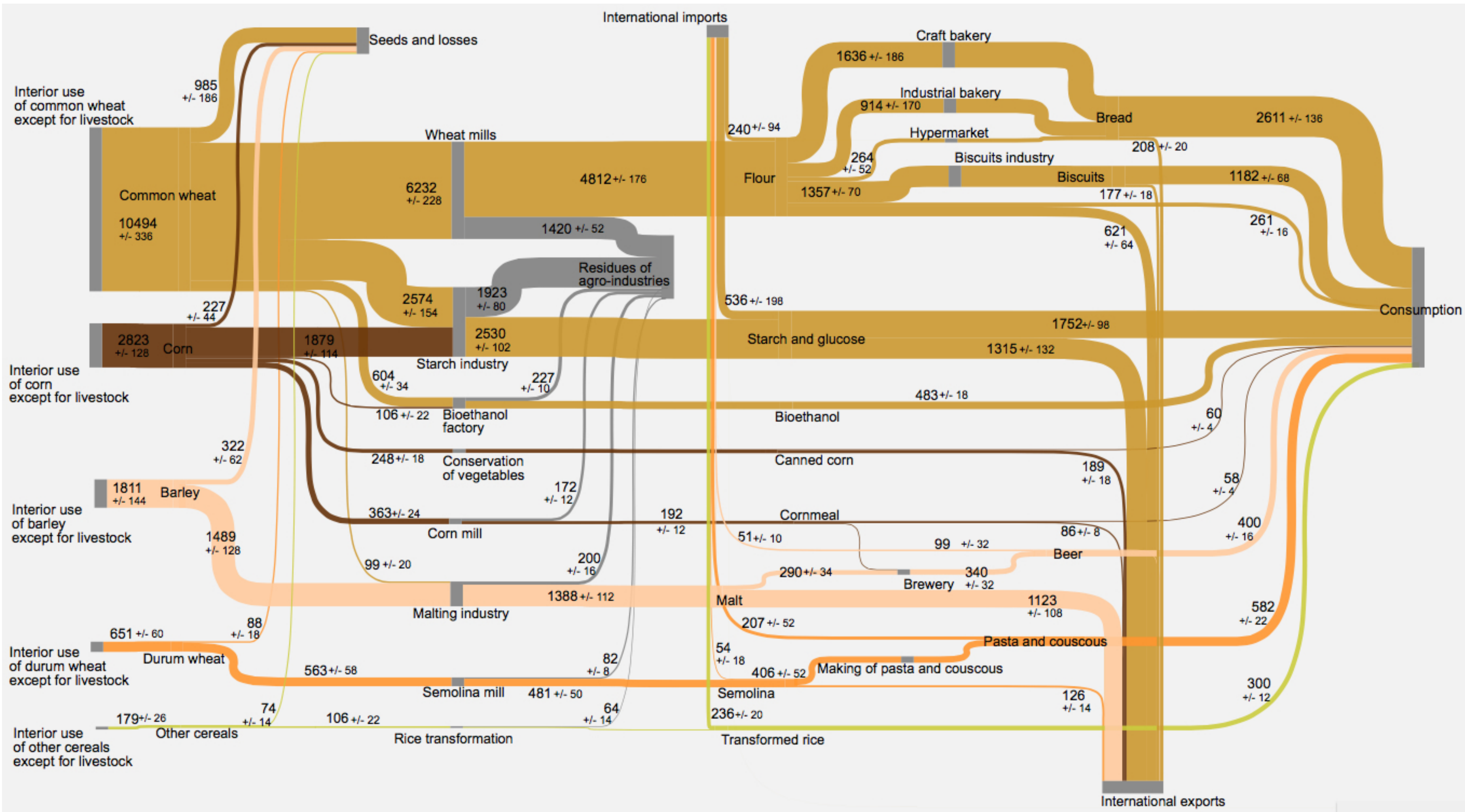

Figure 5: Cereals MFA at the scale of France: interior uses. Results are shown in kilotonnes for an average year over the period 2001-2009.

Figure 5 shows the interior use of each cereal along with imports and exports of transformed products, until final human consumption on the territory. Starch and wheat mill industries clearly stand out as the two main supply chains with respectively 6.2 Mt and 4.4 Mt of grain (wheat and corn) processed. They also produce most of the by-products (3.3 Mt or 81% of the residues). Then comes the malting industry with about 1.6 Mt of barley processed. Other supply chains (bioethanol, pasta and couscous, rice, canned corn, cornmeal) are less significant although together, they add up to 2 Mt[12]. On the imports side, the main flows correspond to flour, starch and glucose, pasta and rice, adding up to 1.1 Mt or 85% of the total imports of transformed products. On the exports side, the main flows correspond to starch and glucose, malt and flour adding up to 2.9 Mt or 78% of the total exports of transformed products. On the consumption side, the main flow corresponds to bread (with 2.6 Mt or 34%), starch and glucose (with 1.8 Mt or 23%), and biscuits (with 1.2 Mt or 16%). Pasta, beer, rice, bioethanol, flour, canned corn add up to 2.2 Mt. 83% of cereals are consumed through food and drink products and 17% through other industrial products[13]. All these figures provide convenient points of comparison for sub-national geographic levels.

500 Monte-Carlo simulations were conducted for the national model. On average, convergence is observed after 50 simulations: after that the increase of the standard deviation is smaller than 5%. According to the Monte-Carlo process, the range of coefficients of variation goes from 1% to 20%, small flows having a larger relative interval of confidence (i.e. a bigger relative uncertainty) in the general case. The output uncertainty has been reduced compared to the input uncertainty through the enforcement of the constraints, for instance wheat production uncertainty (expressed as the coefficient of variation) goes from 2% in the input to 1% in the output. Finally, we checked that each output value belong to the 95% confidence interval of the input.

Figures 12, 13, 14, 15 and 16 in supplementary materials show MFAs of five regions (among the 22 computed) each of which present a specific profile (producing region, livestock region, region with a large transformation activity, exporting region...). Considering the whole dataset, figure 6 show the most important flows accross regions. 3 types of flows stand out: most of them are linked to international exports, some other to livestock activities in Bretagne and the rest to transformation activities in

[12]Bioethanol production increased a lot from the end of the 2000-2010 decade: in 2013, about 2.2 Mt of cereals were used for this purpose, compared to the 0.5 Mt that appear in our results for the 2001-2009 yearly average.

[13]Following Passion-Céréales (2013), we consider that half of the starch production serves non-food purposes.

Nord-Pas-de-Calais. These flows result from the model, they are not the mere visualization of the trade database. Firstly, the model output flows distinguish between products that are otherwise grouped in the trade classification: for instance common and durum wheat as well as residues and livestock feed are initially grouped. Secondly, given their high uncertainty compared to other flows (e.g. production), output inter-regional trade flows sometimes differ significantly from input values: for instance the original database doesn't mention any export above 500 kt from the Centre region while the map shows 4 flows leaving this region.

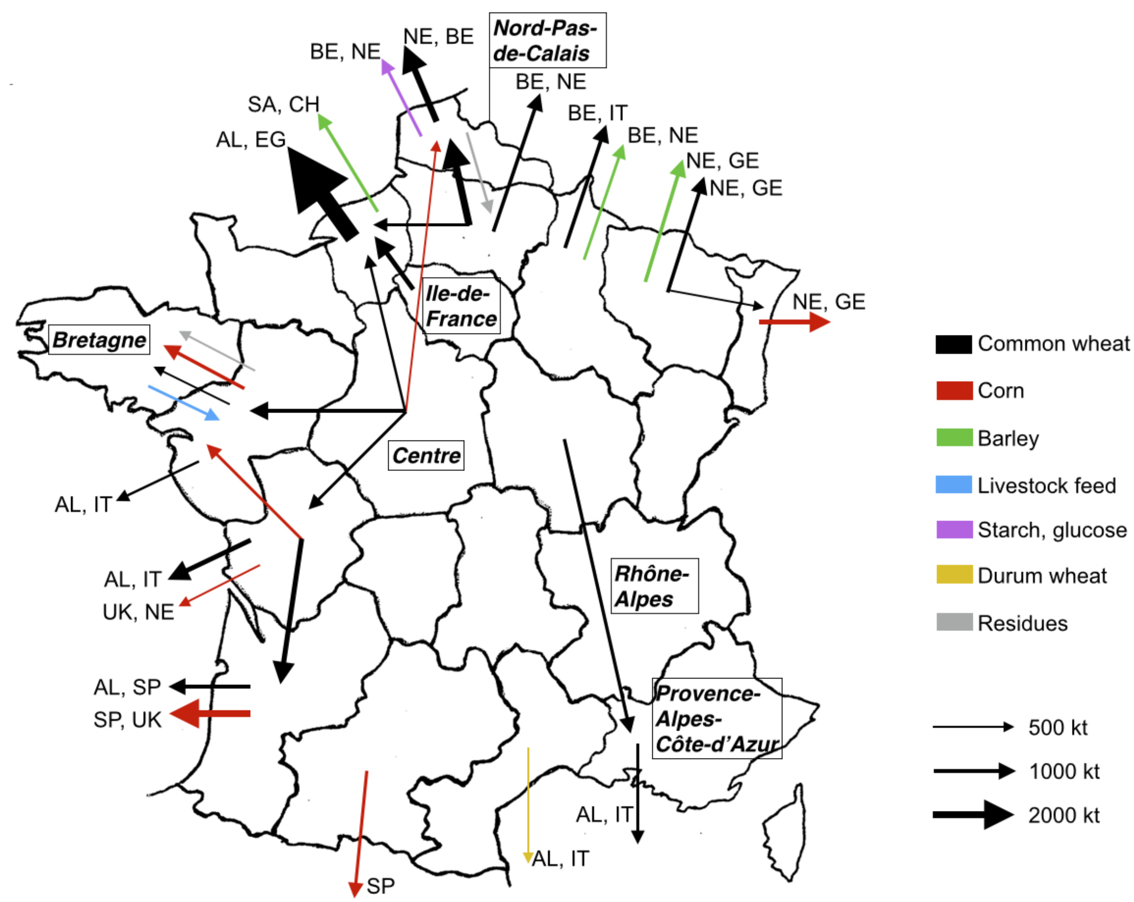

Figure 6: Flows of cereals > 500 kt/year (average during the 2001-2009 period). The main two countries of destination are shown for each international export flow. AL: Algeria, BE: Belgium, CH: China, EG: Egypt, GE: Germany, IT: Italy, NE: Netherlands, SA: Saudi Arabia, SP: Spain, UK: United Kingdom.

3.2. Multi-scale analysis

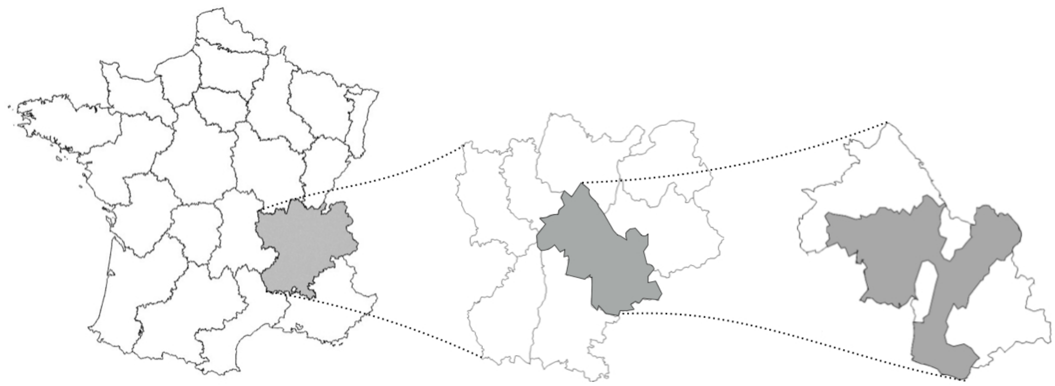

Figure 7: Nested territories under study. From let to right: France, Rhône-Alpes région, Isère départment and the territory of the SCOT of Grenoble.

Territory	**Area (km^2)**	**Population (thousands of inhabitants in 2007)**
France (metropolitan area)	547030	61796
Rhône-Alpes region	44749	6066
Isère department	7882	1179
SCOT of Grenoble	3720	714

Table 7: Surface and population of the four territories under study.

We show diagrams in an aggregated form in order to make the comparison between geographical scales clearer[14]. As indicated in section 2.1.4, results at the level of the Scot (that is, below the level of the département) are not obtained through the usual optimization process and only show net trade. Results for the Isère département are skipped, because they were close to what is observed at the Scot level, but are available upon request.

[14]The graphical scale (i.e. width of line per kt) is different in diagrams 8, 9 and 10 in order to improve the readability of the figures.

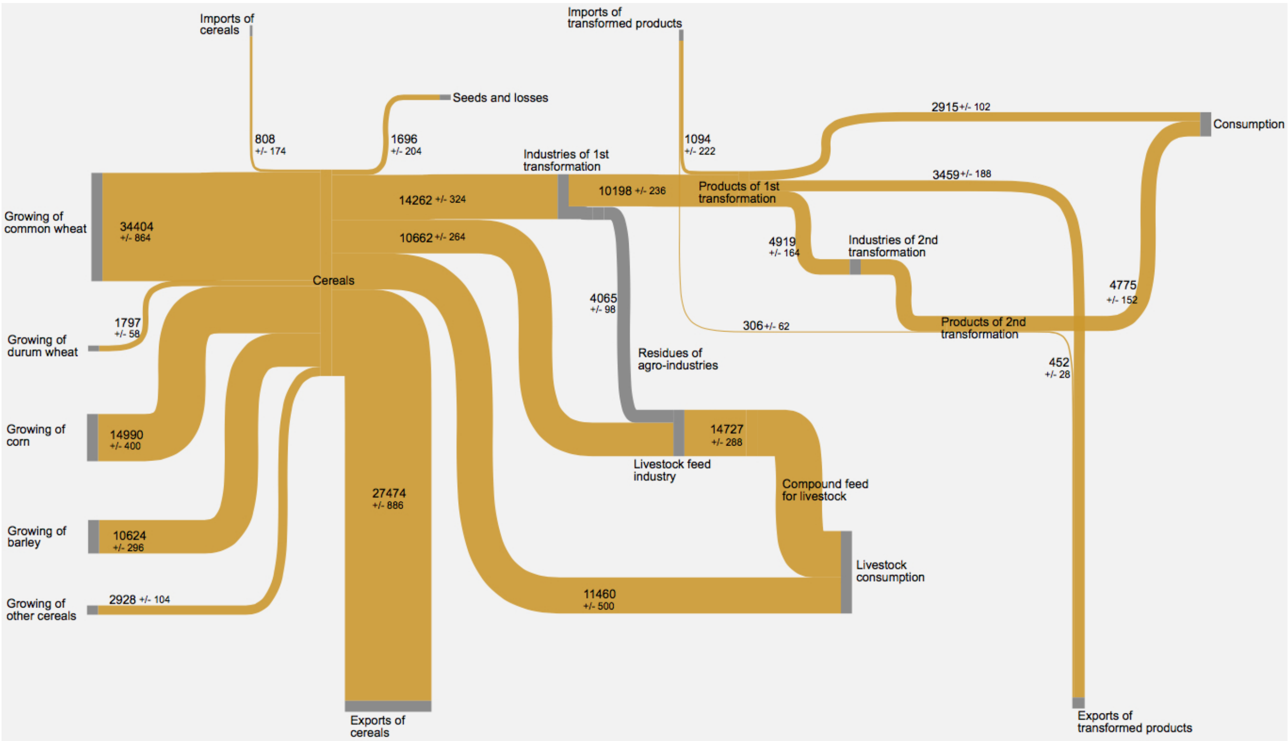

Figure 8: Cereals MFA at the scale of France: aggregated results shown in kilotonnes for an average year over the period 2001-2009.

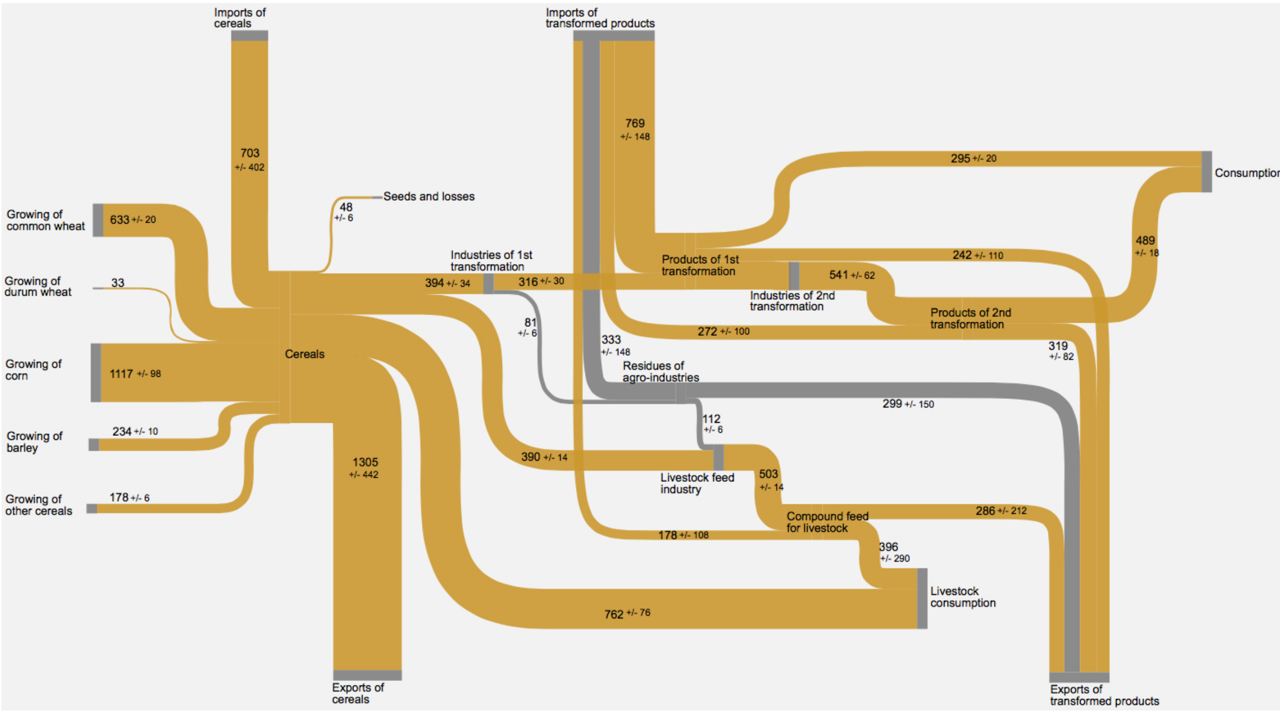

Figure 9: Cereals MFA at the scale of the Rhône-Alpes region: aggregated results shown in kilotonnes for an average year over the period 2001-2009.

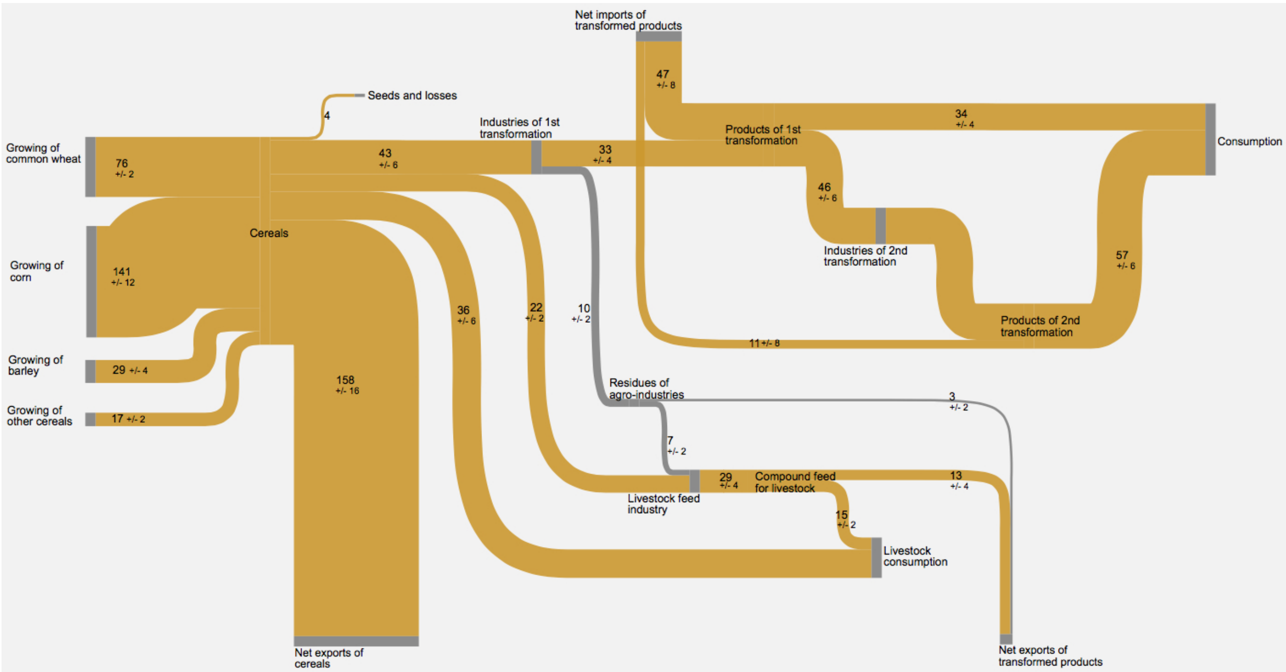

Figure 10: Cereals MFA on the territory of the SCOT of Grenoble: aggregated results shown in kilotonnes for an average year over the period 2001-2009.

The comparison of figures 8 and 9 shows that the supply chain's structure at the level of France and Rhône-Alpes are very different[15]. Indeed, unlike France:

- With a yearly average of 1.1 Mt of grains produced, corn is the most commonly grown cereal in Rhône-Alpes (51% of the total cereal production) before common wheat (29%),
- The region is not caracterized by a significant net export capacity, human and livestock consumption almost adding up to local production, however, inter-regional trade has a important role in the working of the supply chain. In particular, the region is a net exporter of corn, inter-regional exports being the biggest outlet of the corn supply (with 55%), whereas it is a net importer of common wheat (38% of the supply comes from outside the territory),

[15] A few elements also come from the detailed results that are not shown here.

- Many industries, such as the starch industry, are not represented in the region, which leads to significant imports of transformed products (in fact, regional industries almost exclusively process common and durum wheat).

100 Monte-Carlo simulations were run at the regional level. On average, convergence is observed after about 50 simulations. Each flow from one region to another has been computed by the model. We however only show aggregated results because they come with a smaller uncertainty range. As we can see on figure 9, uncertainty ranges of trade flows (even aggregated) are usually quite large. For instance the 95% confidence interval of imports of cereals indicates that the flow can reasonably take values from 301 kt to 1105 kt, the most likely being 703 kt. Of course this reflects the choices made for the uncertainty of input data, where region-to-region flows were given a high uncertainty for the reasons discussed in section 2.2.7.

If we now turn to the comparison of the Rhône-Alpes and of the Scot of Grenoble's supply chains, we can see that they share many characteristics. One of the possible explanation is that the territory of the Scot is a small image of the region itself, since it comprises both mountain and plain areas. Two differences are however worth pointing out: the relative net exports capacity of the Scot is larger than the region's, and contrarily to what happens in Rhône-Alpes, in the Scot, human consumption is larger than livestock consumption. Corn is the most commonly grown cereal in the Scot whereas wheat is the only cereal processed for human consumption purposes. This implies that the territory depends on imports for the supply of many transformed products. This is not necessarily problematic in itself (the smaller the area the less likely it is to be self-sufficient), but we point out that the multi-scale analysis provides information, e.g., on the range of scale this situation can be found.

3.3. Potential interest for practical policy-making

The national MFA as well as the study of interregional flows points to the fact that the cereals supply chain is export-oriented. The fact most exported goods are raw materials can raise the question of lost added value and employment on the national territory. Furthermore, being able to compare regions is important for national objectives. For instance, it makes it possible to assess the pros and cons of regional specialization strategies on the three fronts of sustainability (economic, social and environmental).

From another angle, the type of tool described here is potentially helpful for a better integration of the different levels of decisions through the ability to analyze more and more detailed geographical scales. In the case of France, various administrative levels have leverage on some parts of the supply chain, and each one on a different aspect. For instance, local (group of cities) levels can foster or discourage the development of certain type of activities, either through subsidies, public orders (e.g. organic food in schools) or by administrative authorizations. The regional level is often in charge of coordinating local initiatives while the global strategy and objectives are established at the national level. A multi-scale tool can help in identifying more efficiently the most appropriate type and level of decisions for a given objective.

Generally speaking, through the analysis of the most important supply chains present at the various geographic scales (a substantial endeavor in itself) one opens up the possibility of addressing a number of social and environmental issues and of identifying potential lock-ins and/or leverages for a sustainability transition; we briefly mention a few key questions here. What are the critical supply chains in terms of employment for a given territory? What are their weaknesses and opportunities relatively to the territory's resources (in a wide meaning of the word)? What type of environmental impacts are associated to them, and where do they occur (is the territory externalizing major impacts)? Regarding the case of cereals, energy use / emission of greenhouse gases, use of water and use of pesticides are of particular interest. A production map coupled with ecosystem services analyzes[16] will show what are the critical areas/productions, while the supply chain point of view will show how impacts can be shared between producers and consumers. A supply chain perspective may also help decision-makers anticipate climate change impacts (e.g., how a change in cereal production type and pattern affects employment and/or consumption on the territory?) Conversely, how can consumer-driven sustainability demands (local production, for example, or reduction of demand for meat-based products) affect existing supply chains and promote new ones, both in terms of employment and (local and distant) environmental impacts? Addressing a number of these questions will of course require a scenario approach, or at least an analysis of contrasted options.

4. Conclusion

Regarding our first objective, that is assessing the feasability of constructing non-survey MFA at local scales, we argue that the proposed methodology is an efficient investment: efforts are needed to design the initial model (in relation to the downscaling objective) but results are then available almost directly for any territory covered by the data. Moreover, the data reconciliation process provides consistent and comparable results among territories. Secondly, we tested our multi-scale model and analyzed its results in the case of the cereals supply chain of four nested territories: France, the Rhône-Alpes région, the Isère département and the SCOT of Grenoble. This example shows that it is possible to identify the key differences in local supply chains and to understand how they are currently articulated.

Uncertainties are unavoidable in this kind of studies and it is important to assess them (Rechberger et al., 2014). We tried to do so, although acknowledging that the evaluation itself is still imperfect. In order to improve it, at least

[16] One author is involved in this type of program which critically complements the one undertaken here.

three elements would be useful: an iteration with local stakeholders and experts during the design of the model and the choice of data inputs, a better knowledge on the interval of confidence of statistical data used as input (work is for instance under way regarding road freight statistics), and finally, a sensitivity analysis to understand the weight of each input variable in the results of the model.

As underlined in the introduction, we consider MFA as a first step towards a broader analysis of economic, social and environmental aspects of local supply chains. Additional work has to be conducted to reach this goal. For instance, regarding environmental aspects, studying the coupling between material flows and the associated major environmental footprints (energy use, greenhouse gases emissions, water use, use and emission of pollutants...) provides relevant leads for our future investigations of this topic. MFA helps to bridge the geographical gap between producers and consumers and can provide good insights on their shared responsibility.

Calame and Lalucq (2009) argue that subnational territories and supply chains are the two key players for organizing a sustainable society in the 21^{st} century thus replacing the the couple state - company, which played a pivotal role in the 20^{th} century, but which they find ill-suited to face the new challenges of sustainability). In their opinion, they could organize both territorial coherence (from city to regional scale) and production chains. There are several underlying ideas to these statements. Firstly, by insisting on supply chains rather than on the companies, one brings the collaborative aspect of exchanges to the forefront to balance the competitive aspects of free markets. Secondly, the focus on territories is driven by the necessity of building on local strengths to balance local weaknesses in the undertaking of a sustainability transition. Finally, local/regional levels are more reactive, and closer to actual social needs and environmental threats, although of course a multiplicity of approaches targeted at the whole spectrum of decision scales is needed to address sustainability issues.

The present MFA study is one of the tools that can be used to foster such a view, as it has the potential to meet decision-makers concerns by providing key information on local supply chains viewed from the economic (creation of wealth), social (local employment) and environmental (flows of environmental pressures from producers to consumers) perspectives. In a time when the fragility of the complex globalized system makes it mandatory for all to strengthen their capacity of absorbing exogenous shocks, the development of such tools at the service of subnational institutions is a necessity.

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Supplementary Material

A. Additional tables

Figure 11: Supply (above) and Use (below) tables of the study. White cells have to be filled, grey cells mean the corresponding quantity is null. At subnational scales, additional columns for inter-regional trade are added. The starch and glucose category encompass both mid-products and finished products containing those substances. Indeed, the number of products containing starch derivatives is huge, both in food and in non-food industries (chemistry, textile etc.) and tracking them is beyond the scope of this study.

Conversion	Factor
From common wheat to flour	0.77
From durum wheat to semolina	0.86
From maïze to cornmeal	0.53
From common wheat to starch	0.53
From maïze to starch	0.63
From barley to malt	0.88
From wheat or maïze to bioethanol	0.68

Table 8: Conversion factors (kg of cereal output per kg of cereal input) deducted from the cereals inter-profession yearly report.

Year	Production	Net imports	Stock variation	Apparent consumption
2001	182%	-83%	1%	100%
2002	202%	-97%	-5%	100%
2003	182%	-94%	12%	100%
2004	212%	-102%	-10%	100%
2005	190%	-96%	6%	100%
2006	186%	-89%	3%	100%
2007	173%	-72%	-1%	100%
2008	192%	-87%	-5%	100%
2009	204%	-99%	-5%	100%
Period average	**191.5%**	**-90.9%**	**-0.6%**	**100%**
	64 453 kt	**-30 592 kt**	**202 kt**	**33 659 kt**

Table 9: Contribution of production, trade and stock variation to apparent consumption. Net imports includes primary and transformed products, expressed in weight of grain equivalent. When all terms are positive, production and net imports contribute positively to apparent consumption contrary to stock variation (final stock - initial stock).

Animal or product	Embodied cereals (Mt)	Corrected embodied cereals (Mt)
Pigs	6.3	7.1
Poultry	5.5	6.2
eggs	1.3	1.5
chickens and turkeys	3.1	3.5
others	1.1	1.2
Cattle	7.1	8.0
cattle for milk	3.5	4.0
cattle for meat	3.6	4.1
Other	0.7	0.8
Total from nutrition model	19.6	22.2
Total from national accounts	22.2	
Scaling ratio	1.13	

Table 10: Livestock feed in France

Animal or product	Embodied cereals (kg)	Ratio applied on...
Piglet	71	production
Pig	255	production
Egg for consumption	0.1	production
Egg to be hatched	0.257	production
Chicken, duck, turkey, goose, guinea fowl	see table12	production (balanced by average carcass weight)
Rabbit	2.64	production
Horse	730	livestock
Lamb	11.35	production
Milking ewe	60.83	production
Goat	0	livestock
Milking cow (milk)	see table 13	livestock (balanced by average milk production per cow)
Nursing cow (meat)	303	livestock
Renewal heifer 1 to 2 years old (milk and meat)	383	livestock
Renewal heifer older than 2 years (milk and meat)	511	livestock
Heifer from 6 months to 1 year (meat)	386	production
Heifer 1 to 2 years old (meat)	824	production
Heifer older than 2 years (meat)	1043	production
Males from 6 months to 1 year (meat)	325	production
Males from 1 to 2 years (meat)	800	production
Males older than 2 years (meat)	558	production

Table 11: Estimation of livestock cereals intakes. Calculation by the authors, based on Drogoul et al. (2004). Production refers to the number of animals slaughtered a given year. Livestock refers to the number of living animals at the end of the year. Care was taken in order to avoid double-counting. For instance intakes of poultry does not include the cereals fed to the laying hen (which are considered separately under the category ”egg to be hatched”). Moreover for each category of animal, either the lifetime approach or the annual approach is used. The underlying hypothesis that we make by summing up the two approaches is that stock variation is negligible.

carcass weight (kg)	**cereals feed (kg)**
0.75	1.5
1.1	2.4
1.4	3.2
1.7	4.5

Table 12: Chicken lifetime cereals intakes depending on carcass weight. After Drogoul et al. (2004). A linear interpolation is conducted for weight values inbetween and after.

Maximum daily production without compound feed	**Quantity of compound feed per additionnal daily litter of milk**	**% of cereals in the compound**
10 L	0.4 kg/L	60%

Table 13: Hypothesis used to estimate cereals feed of milking cows depending on milk production quantity. It is assumed that additional nutritional feed is needed (60% cereals, 40% soy cakes) for each additional litter of milk above 10 L per day during the lactation period (10 months) (Drogoul et al., 2004).

Region name	**Presence of major harbors exporting cereals**	**Total exports before redistribution (kt)**	**Total exports after re-distribution (kt)**	**Absolute difference (kt)**	**Relative differ-ence**
Haute-Normandie	Rouen	5788	5901	+113	+2%
Aquitaine	Bordeaux, Bayonne	2647	2707	+60	+2%
Nord-Pas-de-Calais	Dunkerque	2149	2345	+196	+9%
Poitou-Charentes	La Rochelle	2637	2150	-487	-18%
Lorraine		1880	1781	-99	-5%
Champagne-Ardenne		1633	1578	-55	-3%
Picardie		1523	1486	-37	-2%
Provence-Alpes-Côte-d'Azur	Marseille	606	1204	+598	+99%
Languedoc-Roussillon	Port-la-Nouvelle, Sète	1066	1203	+137	+13%
Alsace		1161	1133	-28	-2%
Midi-Pyrénées		1150	1115	-35	-3%
Pays-de-la-Loire	Nantes-Saint-Nazaire	1140	1083	-57	-5%
Bourgogne		759	701	-58	-8%
Centre		707	680	-27	-4%
Rhône-Alpes		464	368	-96	-21%
Ile-de-France		536	346	-190	-35%
Basse-Normandie	Caen	265	323	+58	+22%
Auvergne		103	101	-2	-2%
Franche-Comté		76	74	-2	-3%
Bretagne		10	15	+5	+50%
Limousin		4	4	+0	+0%

Table 14: Impact of the maritime exports redistribution operation on the total international exports of regions (all modes of transports included). The regions without a harbor tend to lose some exports to the benefit of the regions with a harbor. The most impacted region is Provence-Alpes-Côte-d'Azur whose exports increase twofold with an additional 600 kt.

Region name	Gap with the average bread consumption in France
Ile-de-France	-19%
Champagne-Ardenne	+10%
Picardie	+9%
Haute-Normandie	+9%
Centre (FR)	-1%
Basse-Normandie	+5%
Bourgogne	+1%
Nord - Pas-de-Calais	+5%
Lorraine	+11%
Alsace	-2%
Franche-Comte	+9%
Pays de la Loire	-1%
Bretagne	-2%
Poitou-Charentes	+9%
Aquitaine	+5%
Midi-Pyrenees	+5%
Limousin	+7%
Rhone-Alpes	-2%
Auvergne	+9%
Languedoc-Roussillon	+5%
Provence-Alpes-Cote-d'Azur	-12%
Corse	+9%

Table 15: Bread consumption variability among French regions in the mid 1990's (Babayou et al., 1996), results partially reconstructed by the authors. Bread is by far the main form under which cereals are consumed in France, which means that a 20% difference with the national average, as in the case of the parisian region, can impact the cereals' MFA significantly.

B. Handling the correspondence between production and transport classifications

There exists no trade database at subnational scales that perfectly matches our products classification. Therefore, a few traded categories are more aggregated than our own categories. For instance the *wheat* category in the transport database includes both our *common wheat* and *durum wheat* categories. Table 16 in this annex shows the full correspondence. Below we use the notation agg_k to refer to a group of aggregated goods (e.g. *wheat*).

After modification, the new objective function which is applied to subnational scales is the following:

$$
\begin{aligned}
\min \quad \Big(& \sum_a \sum_i \sum_j \frac{(\hat{V}^a_{ij} - V^a_{ij})^2}{(\sigma^a_{Vij})^2} + \sum_a \sum_i \sum_j \frac{(\hat{U}^a_{ij} - U^a_{ij})^2}{(\sigma^a_{Uij})^2} \\
& + \sum_a \sum_{i \notin agg_k \forall k} \frac{(\hat{I}^a_i - I^a_i)^2}{\sigma^2_{Ii^a}} + \sum_a \sum_k \frac{(\hat{I}^a_{agg_k} - I^a_{agg_k})^2}{\sigma^2_{I^a_{agg_k}}} \\
& + \sum_a \sum_{i \notin agg_k \forall k} \frac{(\hat{E}^a_i - E^a_i)^2}{\sigma^2_{Ei^a}} + \sum_a \sum_k \frac{(\hat{E}^a_{agg_k} - E^a_{agg_k})^2}{\sigma^2_{E^a_{agg_k}}} \\
& + \sum_a \sum_b \sum_{i \notin agg_k \forall k} \frac{(\hat{Ir}^{a,b}_i - Ir^{a,b}_i)^2}{\sigma^2_{Ir^{a,b}_i}} + \sum_a \sum_b \sum_k \frac{(\hat{Ir}^{a,b}_{agg_k} - Ir^{a,b}_{agg_k})^2}{\sigma^2_{Ir^{a,b}_{agg}}} \\
& + \sum_i \frac{(\hat{C}^a_i - C^a_i)^2}{\sigma^2_{C^a_i}} \Big)
\end{aligned}
$$

with:

V^a_{ij}	supply of product i by industry j in region a,
I^a_i, E^a_i	international imports/exports of product i to/from region a,
$Ir^{a,b}_i = Er^{b,a}_i$	imports of product i to region a from region b
	equal exports of product i from region b to region a,
$\hat{X}_{agg_k} = \sum_{i \in agg_k} \hat{X}_i^{\text{degen}}$	where X represents matrices $\hat{I}$, $\hat{E}$ or $\hat{Ir}$

The drawback here (as indicated by the *degen* superscript), is that this triggers degeneracy: there is an infinity of possible solutions for each $\hat{X}_i^{\text{degen}}$ although each $\hat{X}_{agg_k}$ is unique, and the result provided by the algorithm will depend on the solver's implementation and on the initialisation of variables. This is not satisfactory, even if the infinity of solutions is in practice bounded thanks to the constraints. We therefore conduct a second optimization that aims at obtaining a unique solution. A new rule (hypothesis) to make an allocation to each product belonging to an aggregate is needed. We choose to minimize the square values of imports and exports, while respecting the output of the first step, which leads to a balanced allocation inside each aggregated group.

The second optimization under constraint is therefore:

$$\min\Big(\sum_a\sum_k\sum_{i\in agg_k}(\hat{I}_i^a)^2+\sum_a\sum_k\sum_{i\in agg_k}(\hat{E}_i^a)^2+\sum_a\sum_b\sum_k\sum_{i\in agg_k}(\hat{Ir}_i^{a,b})^2\Big)$$

subject to the following constraints:

All terms are positive:

$$\hat{X}\geq 0 \qquad \text{where } X \text{ represents matrices } I, E \text{ or } Ir,$$

For each region, international imports of all products belonging to an aggregate equal the aggregated imports found in the first step of the optimization:

$$\sum_{i\in agg_k}\hat{I}_i^a=\hat{I}_{agg_k}^a \qquad \forall a,\ \forall k$$

Same for international exports:

$$\sum_{i\in agg_k}\hat{E}_i^a=\hat{E}_{agg_k}^a \qquad \forall a,\ \forall k$$

Same for inter-regional trade:

$$\sum_{i\in agg_k}\hat{Ir}_i^{a,b}=\hat{Ir}_{agg_k}^{a,b} \qquad \forall a,\ \ \forall b,\ \ \forall k$$

Resource equals use constraint:

$$\begin{aligned}\hat{I}_i^a+\hat{Ir}_i^{a,b}-\hat{E}_i^a-\hat{Ir}_i^{b,a}&=\hat{I}_i^{a,degen}+\hat{Ir}_i^{a,b,degen}-\hat{E}_i^{a,degen}-\hat{Ir}_i^{b,a,degen}\\&=\sum_j\hat{U}_{ij}^a+\hat{C}_i^a-\sum_j\hat{V}_{ij}^a \qquad \forall a,\ \forall i\in agg_k,\forall k\end{aligned}$$

Geographical aggregation constraint for international trade:

$$\sum_a\hat{X}_i^a=\hat{X}_i^{fr} \qquad \forall i\in agg_k,\forall k \qquad \text{where X represents vectors } I \text{ or } E.$$

We point out that this process is transparent when results are presented in aggregated forms, such as in figures 8, 9 and 10: everything appears as if only the first optimization had been done.

Product	**NST code(s)**	**NST name(s)**
Common wheat	011	Wheat, spelt and meslin
Durum wheat	011	Wheat, spelt and meslin
Maize	015	Maize
Barley	012	Barley
Other cereals	013 - 014 - 019	Rye - Oats - Other cereals
Flour	161	Flour, cereal meal and groats
Residues	179	Bran, cereal by-products and other animal food
Semolina	161	Flour, cereal meal and groats
Corn semolina	161	Flour, cereal meal and groats
Canned corn	NA	NA
Starch and glucose	895 - 136	Starches and gluten - Glucose, dextrose
Bread	163	Other cereal preparations
Biscuits	163	Other cereal preparations
Compound feed	179	Bran, cereal by-products and other animal food
Pasta and couscous	163	Other cereal preparations
Transformed rice	016	Rice
Malt	162	Malt
Beer	122	Beer made from malt
Bioethanol	NA	NA

Table 16: Correspondence between the NST transport statistics classification (used in the SitraM database) and the product classification used the MFA study (left column). *NA* stands for *Not Applicable* and indicates that no suitable correspondence was found: for those products, the trade data was initially set to zero, before being modified during the data reconciliation process. This hypothesis is conservative in the sense that in minimizes the inter-regional trade of those flows (canned corn and bioethanol).

C. Regional MFA diagrams

We show below the diagrams corresponding to 5 of the 22 regional MFAs computed. They were chosen because they were representative of the variety of regional profiles.

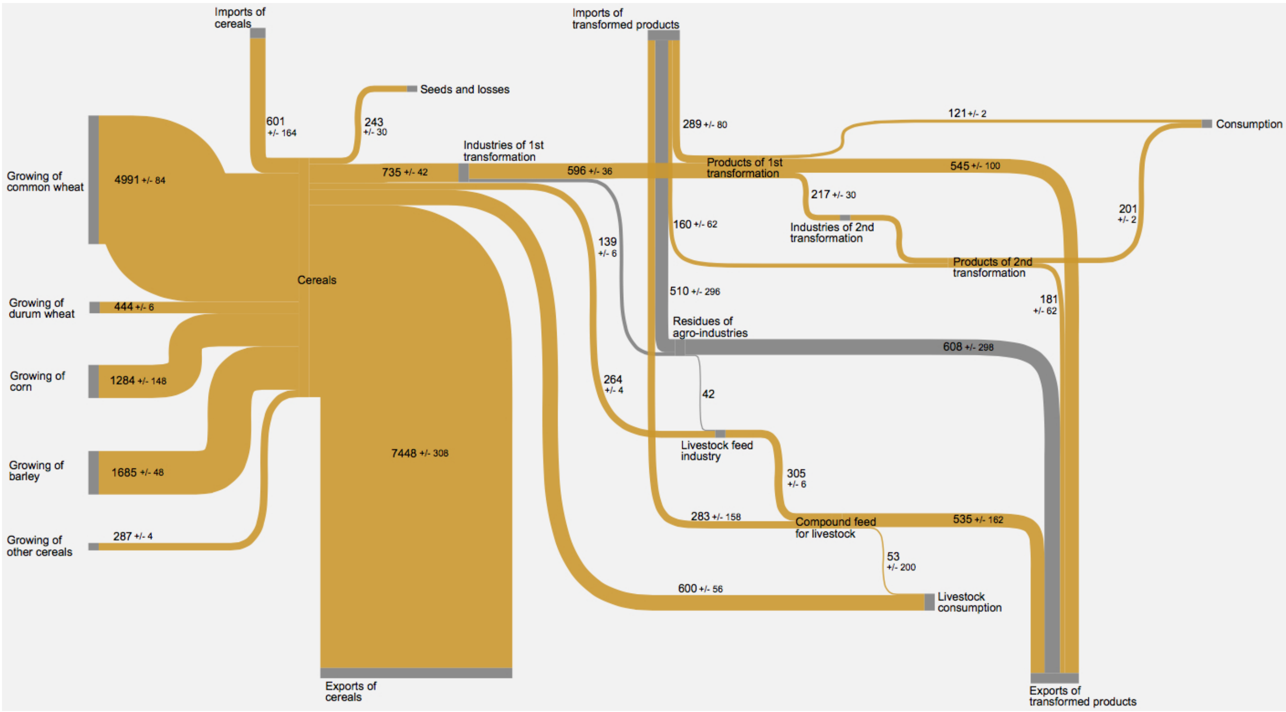

Figure 12: Cereals MFA at the scale of Centre. Results are shown in kilotonnes for an average year over the period 2001-2009. Centre is the largest producer and exporter of cereals in the country.

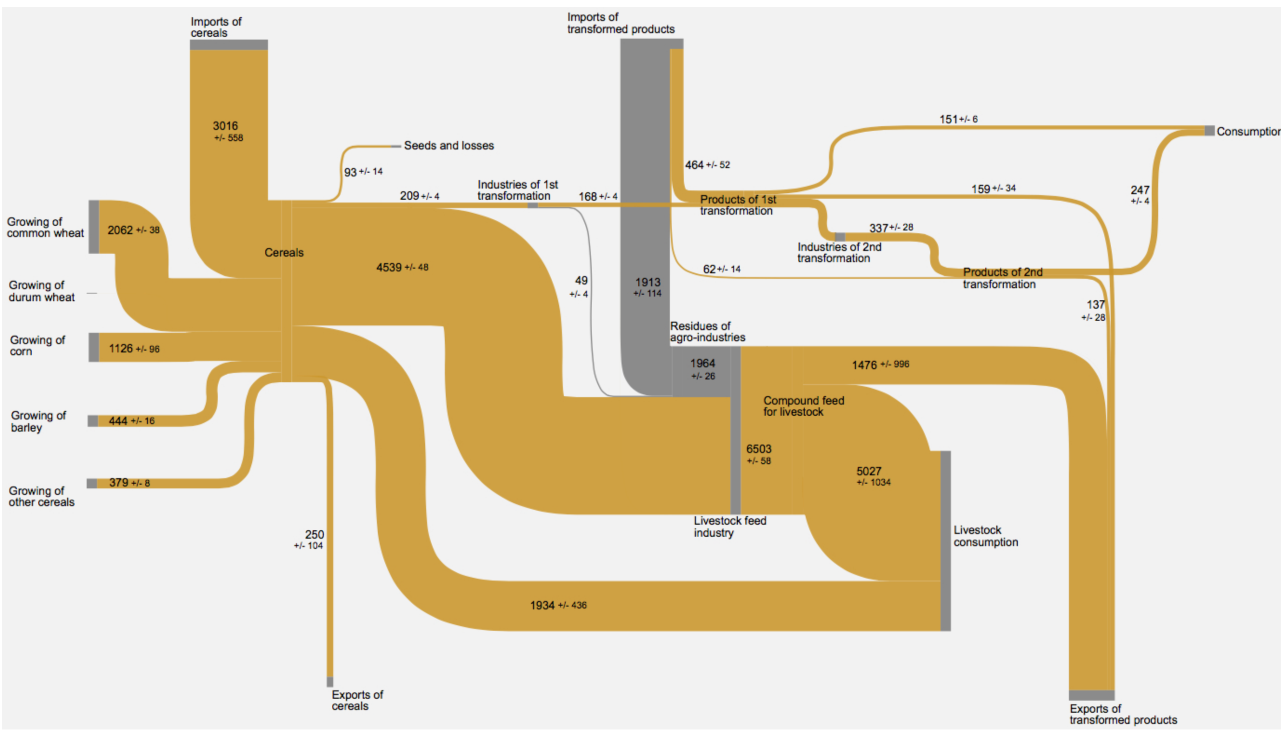

Figure 13: Cereals MFA at the scale of Bretagne. Results are shown in kilotonnes for an average year over the period 2001-2009. In Bretagne most of the cereal supply is dedicated to livestock.

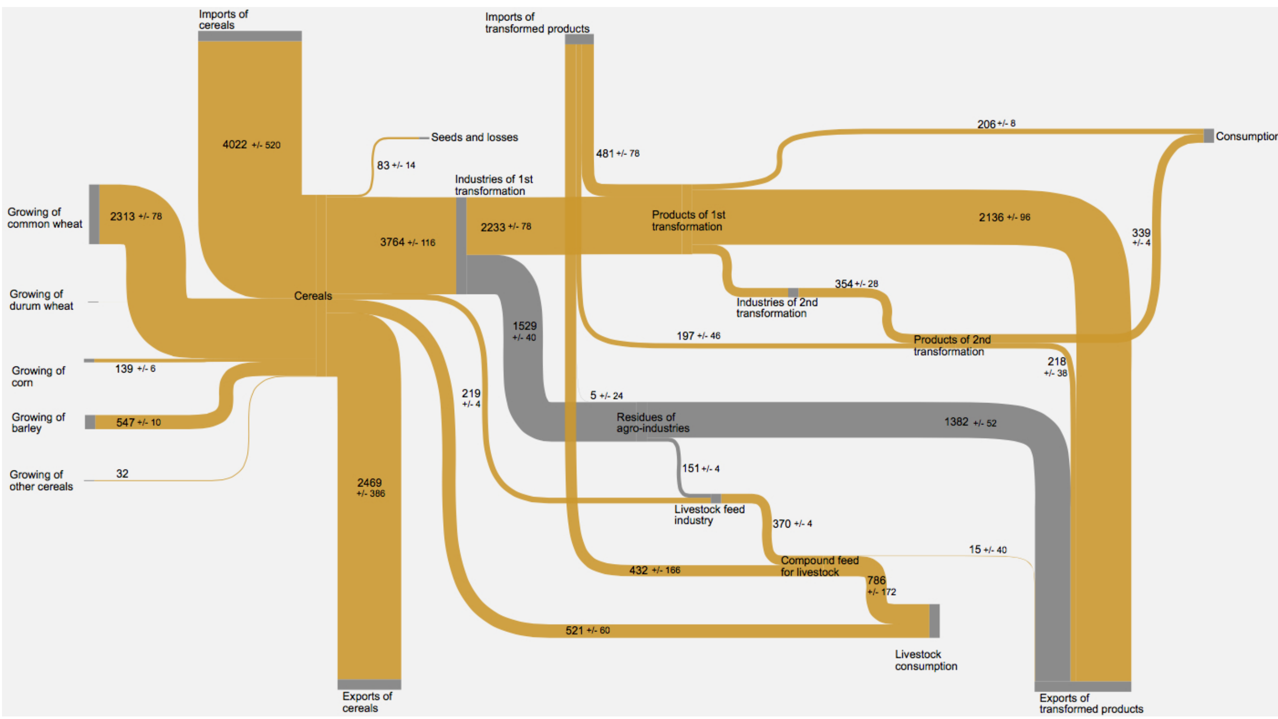

Figure 14: Cereals MFA at the scale of Nord-Pas-de-Calais. Results are shown in kilotonnes for an average year over the period 2001-2009. Nord-Pas-de-Calais has a strong activity of international export and also has the largest transformation industry in the country.

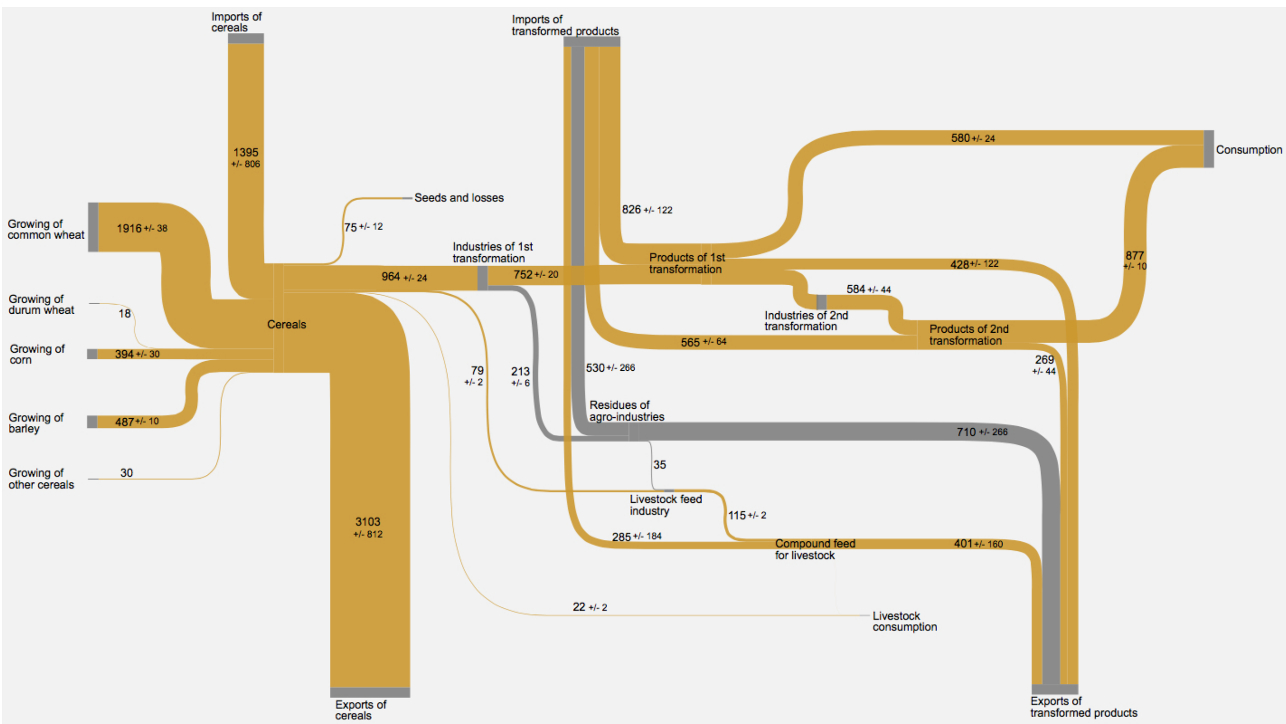

Figure 15: Cereals MFA at the scale of Ile-de-France. Results are shown in kilotonnes for an average year over the period 2001-2009. The Parisian region exports a lot of cereals but also dedicates a large part of the supply to human consumption since it's the most populated area in the country.

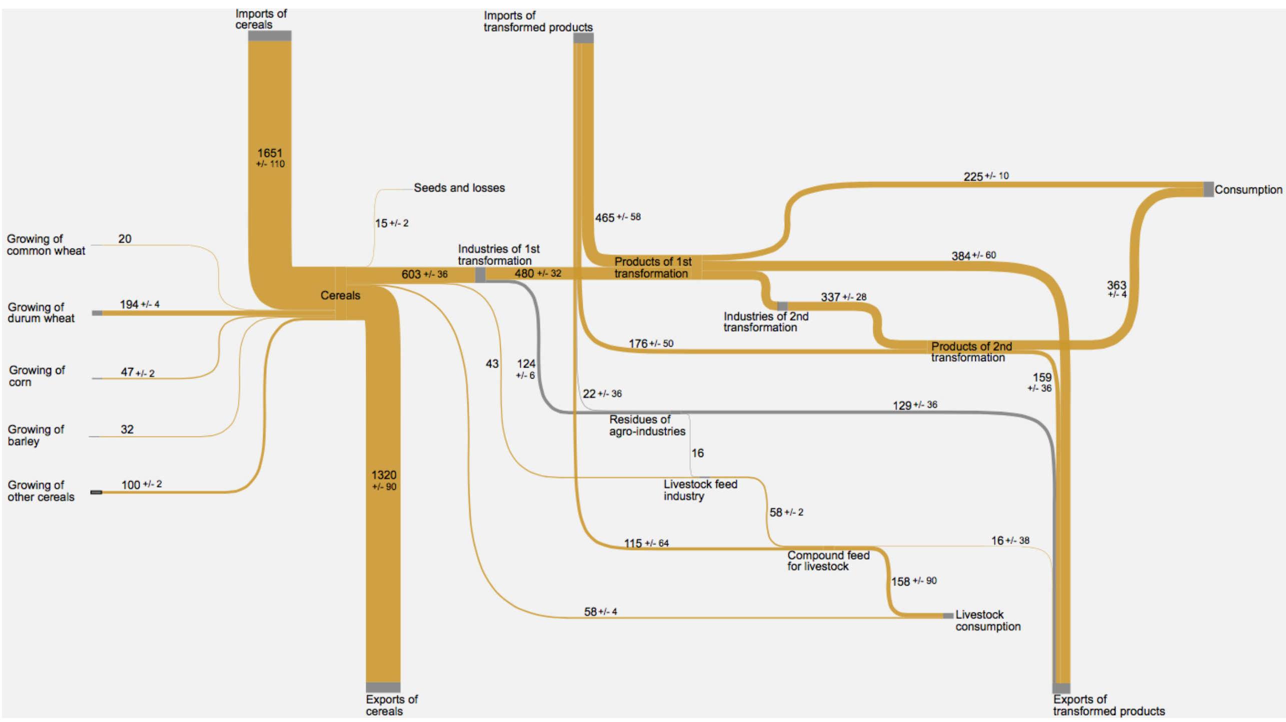

Figure 16: Cereals MFA at the scale of Provence-Alpes-Côte-d'Azur. Results are shown in kilotonnes for an average year over the period 2001-2009. Provence-Alpes-Côte-d'Azur is a small producer but its key role in international exports is clearly shown in the diagram.