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Environmental pressures embodied in the French cereals supply chain

Jean-Yves Courtonne, Pierre-Yves Longaretti, Julien Alapetite, Denis Dupré

1 **Abstract**

2 France is the second largest exporter of cereals in the world. Although the cereals supply chain is an asset
3 for the country's economy and employment, it is at the same time responsible for a number of pressures
4 on the local and global environment including greenhouse gases (GHG) emissions and stresses on water
5 quality and quantity. This article aims at evaluating this situation from an environmental point of view by
6 linking productions occurring in French regions with consumptions occurring in France and abroad. Based
7 on previous work on Material Flow Analysis, we use an Absorbing Markov Chain model to study the fate of
8 French cereals and link worldwide consumptions to environmental pressures along the supply chain, that is,
9 induced by production, transformation or transport. The model is based on physical supply and use tables and
10 distinguishes between 21 industries, 22 products, 38 regions of various spatial resolution (22 French regions,
11 10 countries, 6 continents) and 4 modes of transport. Energy use, GHG emissions, land use, use of pesticides
12 and blue water footprint are studied. Illustrative examples are taken in order to demonstrate the versatility
13 of the results produced, for instance: Where and under what form does local production end up? How do
14 regions compare relatively to their production and consumption footprints? These results are designed to be
15 a first step towards scenario analysis for decision-aiding that would also include socio-economic indicators.
16 Examples of such scenarios are discussed in the conclusion.

17 **Introduction**

18 The producer-centric approach to environmental impacts of economic activities was historically the first
19 developed. Lenzen et al. (2007) suggest it may be because questioning consumer preferences was not in
20 line with a free-market philosophy. A complementary explanation is that the producer's responsibility is the
21 most easily and objectively traceable as it concerns flows that can be physically observed on site; on the
22 contrary, a series of allocation hypotheses are needed in order to trace consumer's responsibility. In today's
23 economy, intensively relying on international trade, environmental accounts from both perspectives are a
24 necessity to guide decision-making and prevent a simple externalization of impacts. In the past two decades,
25 an important research effort was put on the development of Input-Output Analysis (IOA) in order to associate
26 final consumption expenditures of households and administrations with the worldwide production of goods
27 and services they trigger. Of all environmental pressures, greenhouse gases (GHG) emissions were the most
28 studied (Peters and Hertwich, 2006a) (Wiedmann et al., 2010), although research also targeted water use
29 (Guan and Hubacek, 2007), land use (Yu et al., 2013) or material flows (Bruckner et al., 2012) to name
30 only a few. Socio-economical aspects were also studied (Simas et al., 2014). The second path of research
31 to link producer's and consumer's responsibilities is the coupling of Material Flow Analysis (MFA) with

32 Life Cycle Assessment (LCA), or more simply with ratios of pressure intensity (Rochat et al., 2013). This
33 is for instance the approach followed in the classical calculation of the Ecological Footprint (Wackernagel
34 et al., 2005). Each method having its own drawbacks (typically, trade of services is not accounted for in
35 the MFA-based approach, while IOA can sometimes lead to questionable results (Kastner et al., 2014)), the
36 choice between the two relies on the research question and on data availability. Our study is based on supply
37 chain material flows because of our focus on the regional level and of the level of detail we aim at¹.

38 A supply chain is by definition a group of sectors organized to produce, transform and distribute specific
39 goods to consumers. It is therefore an obvious object of study when it comes to analyzing the links between
40 production and consumption. Leigh and Li (2014) propose a literature review on environmental approaches
41 to sustainable supply chain management, that includes environmental management, design for environment,
42 product stewardship, green purchasing, reverse logistics, recycling, reuse and remanufacturing. This body of
43 literature studies the supply chain from a company's perspective. In a complementary way, the present work
44 adopts a territorial point of view and is primarily intended for institutional decision makers at regional and
45 national levels. Cazarro et al. (2014) propose a similar perspective by focusing on footprints and scenario
46 analysis of the agro-industry of a Spanish region. They underline the importance of articulating regional
47 and national strategies, stressing Spanish regions have major competences regarding the local economy
48 and environment. While France remains more centralized than Spain, the jurisdiction of local territories
49 tends to expand. Calame and Lalucq (2009) insists on the pivot role territories and supply chain could play
50 in a transition to sustainability at local, national and international scales, benefiting from both horizontal
51 (territorial coherence) and vertical (chain of production) integration. Moreover, they argue that these two
52 actors are well adapted to a cooperative vision of the economy.

53 The present article is the second step of a project aiming at analyzing local supply chains from an eco-
54 nomic, social and environmental perspective for decision-aiding. Here, our goal is to analyze environmental
55 pressures along supply chains, i.e. from the producer's to the consumer's viewpoint, to see what pressures
56 are internalized or externalized by French regions and foreign countries. This article follows a study which
57 produced Material Flow Analysis (MFA) on every regional level by downscaling the national MFA (Cour-
58 tonne et al., 2015). We shortly present these results in the methodology section as they are the starting point
59 of the present work.

60 Although the methodology developed here could be applied to any supply chain or region, we imple-
61 ment it on the case of the French cereals supply chain. Cereals are, in terms of weight of production the
62 most important agricultural good in France. The supply chain is a significant contributor to the national
63 economy with a turnover of more than 50 billion euros and 500,000 jobs. It is also the largest contributor to
64 the positive trade balance of the country's agro-industrial sector, along with wine (FranceAgriMer, 2012).
65 Orientations for the development of the supply chain were recently proposed by the ministry of agriculture
66 and confirmed this strategic role of exports. The model is focused on French regions: total productions,
67 trade and consumptions of foreign countries are not studied, only the portion linked to the French supply
68 chain is, that is, either imports of French products or exports of local production to France. According to
69 FAO statistics, France was the 7th largest cereals producer in the world in 2011 (after China, the United
70 States, India, Russia, Indonesia and Brazil) but the 2nd largest exporter (after the USA). Our study therefore
71 encompass about 3% of global production and 11% of global trade of cereals.

72 We study five environmental pressures that are especially relevant for the cereals supply chain: energy
73 consumption, GHG emissions, land use, use of pesticides and blue water consumption. Both global (for
74 instance GHG emissions) and local (for instance use of pesticides) environmental pressures were included
75 in order to aim at a holistic view of the situation. A recent assessment of the implementation of the Water
76 Framework Directive in France revealed that rivers' contamination with pesticides was especially high in
77 cereals-growing regions (SOEs, 2015a). With about 90 Mt CO₂ eq., agriculture is responsible for nearly one

78 fifth of French greenhouse gases emissions² (SOeS, 2015b). Transport and of transformation industries are
79 also responsible for emissions through their use of energy. According to Ercin et al. (2012), crop growing
80 accounts for half of the French blue water footprint of production. Cereals represent 59% of this half, corn
81 representing 50% on its own (the last 9% are shared between rice, wheat, triticale, barley and oats). Production
82 of corn ranks first in the causes of water scarcity in the summer months in many regions, especially in
83 Midi-Pyrénées, Aquitaine, Poitou-Charentes and Centre.

84 The first section is dedicated to the presentation of the methodology and of the datasources. We present
85 the results in the second section laying the emphasis on the types of questions can be tackled with the model:
86 *What is the fate of the regional production? What are the supply areas of the regional consumption? What*
87 *pressures are associated to each life-cycle stage? What pressures are embodied in a specific consumption?*
88 *What are the production and consumption footprint of a region? What are the main paths between production*
89 *and consumption? How do regions compare relatively to their per-capita footprint of consumption?* We then
90 discuss the limits and potential leads to improve the model. The concluding section summarizes the main
91 features of the method developed for the present paper as well as some important findings, before outlining
92 how such results can be used for actual decision-help, in particular through the discussion of energy transition
93 and land use scenarios for France at the 2050 time horizon.

94 **Materials and methods**

95 Studying how environmental pressures flow from producers to consumers is done in 3 steps:

- 96 • Reusing and extending an existing MFA model at the level of French regions,
- 97 • Tracking flows downstream using an AMC model with transport sectors,
- 98 • Coupling material flows with associated pressures on the environment all along the supply chain,
99 that is pressures generated for the production of raw materials, pressures generated by transformation
100 industries and pressures generated by freight.

101 Coupling of MFA with Markov chains modeling was for instance previously done by Eckelman and Daigo
102 (2008) (for a discussion on the relationships between AMC, IOA and MFA see Eckelman et al. (2012)).
103 This methodology can be applied to any type of product; here it is specifically applied to the French cereals'
104 supply chain.

105 **An MFA on cereals in every French region**

106 We base the model on previous results of the authors (Courtonne et al., 2015). MFAs on the cereals supply
107 chain in the 22 French regions were produced in the form of reconciled physical supply and use tables by
108 downscaling the national MFA. 19 products (raw materials, intermediate and end-products) and 18 industries
109 were taken into account. The period studied was the annual average between years 2001 and 2009 and is
110 therefore the same in the present article.

111 In this previous work, these MFAs were limited to physical cereal flows, for instance flows of bread were
112 considered because they physically embody cereal grains but flows of livestock products were left out,
113 meaning that the model considered livestock consumption as a final consumption. This makes sense in a
114 pure MFA study but becomes problematic when one is interested in studying and allocating environmental
115 pressures: typically, husbandry regions would then have a high consumption footprint even if their animal
116 products are consumed elsewhere.

117 In order to overcome this issue, three animal products were included in this extension of the model: meat,
 118 milk (including milk products) and eggs. Balanced MFAs at the level of French regions were obtained
 119 using the methodology described in Courtonne et al. (2015) and data sources from the French Ministry of
 120 Agriculture, from customs data and from the SitraM database for inter-regional trade. All details regarding
 121 the classifications used are available in supplementary material.

122 **An AMC model to track flows from producers to consumers**

123 The next step is to study the fate of cereals products and the paths they take in the economy. Typical questions
 124 are: *Where and under what form does a grain of wheat produced in region A end? What productions and*
 125 *transports were needed in order to consume 1 kg of bread in region B?* Here, the two questions respectively
 126 adopt a downstream and an upstream perspective. The AMC model implemented is inspired by the one
 127 proposed by Duchin and Levine (2013). The main difference is that we build the tables directly from our
 128 MFA data and not from Input-Output tables. A smaller difference is in the way we deal with transport sectors
 129 (we associate each transport flow with the product traded whereas they rather model the trade of transport
 130 services between regions).

131 Flows through a (spatialized) supply chain can be seen as changes of state of the quantities involved. Af-
 132 ter being normalized, they can be interpreted as transition probabilities. Note that the underlying assumption
 133 here is a *perfect blend* between local production and imports: without additional information we assume
 134 once a product is available in a region, its use is independent from its geographical origin. As explained
 135 by Duchin and Levine (2010), “for any system represented by n states, the parameters of an AMC are the
 136 probabilities of directly transitioning from one state to another; they are contained in an $n \times n$ transition
 137 matrix M ”. M_{ij} describes the likelihood of transitioning from state i to state j . Therefore the sum of any
 138 row equals 1. State i is called an absorbing state if M_{ii} equals 1, meaning it can no longer be exited. In our
 139 model, this is the case for end-products that are consumed and for losses. The M matrix can be put into the
 140 following canonical form (Kemeny and Snell, 1976):

$$141 \quad M = \begin{pmatrix} Q & R \\ 0 & I \end{pmatrix} \quad (1)$$

142 In equation 1, Q_{ij} represents the proportion of flows in transient state i directly moving to transient state
 143 j . This is the case when an industry supplies a product, when a product is used by an industry and when a
 144 product is exported from one region to another. Similarly, R_{ij} is the proportion of flows from transient state
 145 i directly moving towards absorbing state j .

146 Below we give more details on the content on the Q and R matrices. We define the following elements:

- 147 • $\mathbf{1}$ is a summation vector (column vector filled with 1). Its size is contextual.
- 148 • n is the number of regions.
- 149 • p is the number of products.
- 150 • q is the number of industries.
- 151 • t is the number of transport modes.
- 152 • S^r is the domestic supply matrix of region r of size (p,q) .
- 153 • $\overline{S}^r = S^r \mathbf{1}$ is a column vector representing the local supply of each product whatever the producing
 154 industry.

- 155 • $\overline{(S^r)^T} = (S^r)^T \mathbf{1}$ is a column vector representing the total production of each industry of region r ,
156 whatever the product.
- 157 • U^r is the domestic use matrix of region r of size (p,q) .
- 158 • $\overline{U^r} = U^r \mathbf{1}$ is a column vector representing the use of each product by industries of region r , whatever
159 the consuming industry.
- 160 • $E^{r,s}$ vector of exports from region r to region s of size p .
- 161 • $T^{r,s}$ matrix of transport from region r to region s of size (t,p)
- 162 • $T^r = \sum_s T^{r,s}$ matrix of transport from region r to all other regions.
- 163 • $\overline{T^r} = T^r \mathbf{1}$ is a column vector representing for each transport mode the total transport from region r .
- 164 • C^r is the vector of consumption of region r of size p .
- 165 • Z^r is the vector of total supply of region r of size $q + p + t$.

Vectors Z^r are composed of 3 parts:

$$Z^r = \begin{matrix} 1 \\ q \\ p \\ t \end{matrix} \begin{pmatrix} Z_1^r \\ Z_2^r \\ Z_3^r \end{pmatrix} \quad Z_1^r = \left[\overline{(S^r)^T} \right] \quad Z_2^r = \left[\overline{S^r} + \sum_s E^{s,r} \right] = \left[\overline{U^r} + \sum_s E^{r,s} + C^r \right] \quad Z_3^r = \left[\overline{T^r} \right]$$

166 Matrices $T^{r,s}$ are computed based on 3 elements:

- 167 • $E^{r,s}$ trade flows from region r to region s , not necessarily expressed in real weight, for instance we use
168 the cereals grain equivalent unit, of size $(p,1)$,
- 169 • w vector of conversion ratios from trade unit to real weight, of size $(p,1)$,
- 170 • $D^{r,s}$ matrix representing distances of transport between regions, of size (t,p) : each mode of transport is
171 one row of the matrix and each product is a column. For international flows, we estimate the distance
172 from/to the country of loading/unloading based on the mode of transport. Equation 2 therefore illus-
173 trates the properties of matrices $D^{r,s}$ for international transport. For domestic inter-regional flows, we
174 exploit the SitraM database providing information both in tonnes and tonnes.kms for each good, mode
175 of transport, origin and destination. Hence it is possible to compute average distances (*tonnes.kms /*
176 *tonnes*) for each group defined by a good, mode of transport, region of origin and of destination. These
177 distances are good estimates of distances from facilities to facilities.

178 The following properties only hold when r or s are foreign regions, they don't in the case of French
179 interregional trade:

$$180 \quad D^{r,s} = D^{s,r} \quad D_{m,j}^{r,s} = D_{m,k}^{r,s} \quad \forall \text{ products } j, k \quad (2)$$

The transport matrices, which show results in weight.distances (typically tonnes.kms) are then computed
as follow (note that we use the hat symbol to refer to the diagonal matrix created from a vector):

$$T^{r,s} = D^{r,s} \hat{w} \hat{E}^{r,s}$$

The Q and R matrices presented below are respectively of size $(n.(q+p+t), n.(q+p+t))$ and $(n.(q+p+t), n.p)$. Q can be partitioned:

$$Q = \begin{bmatrix} Q_{11} & \dots & Q_{1r} & \dots & Q_{1n} \\ & & \vdots & & \\ Q_{r1} & \dots & Q_{rr} & \dots & Q_{rn} \\ & & & & \vdots \\ Q_{n1} & \dots & Q_{nr} & \dots & Q_{nn} \end{bmatrix}$$

with

$$Q_{rr} = \begin{matrix} & q & p & t \\ \begin{matrix} q \\ p \\ t \end{matrix} & \begin{pmatrix} 0 & (\hat{Z}_1^r)^{-1}(S^r)^T & 0 \\ (\hat{Z}_2^r)^{-1}U^r & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \end{matrix}$$

and

$$Q_{rs} = \begin{matrix} & q & p & t \\ \begin{matrix} q \\ p \\ t \end{matrix} & \begin{pmatrix} 0 & 0 & 0 \\ 0 & (\hat{Z}_2^r)^{-1}\hat{E}^{r,s} & 0 \\ 0 & (\hat{Z}_3^r)^{-1}T^{r,s} & 0 \end{pmatrix} \end{matrix}$$

R is also partitioned

$$R = \begin{bmatrix} R_{11} & \dots & 0 & \dots & 0 \\ & & \vdots & & \\ 0 & \dots & R_{rr} & \dots & 0 \\ & & \vdots & & \\ 0 & \dots & 0 & \dots & R_{nn} \end{bmatrix}$$

with

$$R_{rr} = \begin{matrix} & p \\ \begin{matrix} q \\ p \\ t \end{matrix} & \begin{pmatrix} 0 \\ (\hat{Z}_2^r)^{-1}\hat{C}^r \\ 0 \end{pmatrix} \end{matrix}$$

181 Then two matrices of interest can be computed, N and B :

$$182 \quad N = (I - Q)^{-1} \quad B = NR \quad (3)$$

183 Each row i of matrix B can be interpreted as the fate of sector/product i . For instance, the B_{ij} term is
 184 the proportion of i that is finally embodied in region-product j . As we will show it in the next section, it is
 185 interesting to aggregate the terms either by product type or by region. If we define the Z vector as equation
 186 4, we can compute matrix $\hat{Z}B$, with the ij^{th} term representing the amount of i finally embodied in region-
 187 product j . Finally, we can compute matrix L^3 as defined in equation 5⁴ and its ij^{th} term will be interpreted
 188 as the amount of i needed in order to consume one unit of region-product j .

$$189 \quad Z = \begin{bmatrix} Z^1 \\ \vdots \\ Z^n \end{bmatrix} \quad (4)$$

$$L = \hat{Z} B \hat{C}^{-1} \quad \text{with } C = \begin{bmatrix} C^1 \\ \vdots \\ C^n \end{bmatrix} \quad (5)$$

Table 1 presents the size of the main variables/matrices used.

Variable	Size	Comment
n	38	22 French regions, 10 countries, 6 continents
p	22	19 cereals products, 3 animal products
q	21	1 livestock farming sector
t	4	sea, road, railroad, river
Q, N	1786, 1786	the Q matrix is sparse
$R, B, \hat{Z}B, L$	1786, 836	the R matrix is sparse

Table 1: Sizes of the model's variables.

191

192 Coupling material flows with environmental pressures

193 *Data sources to inform environmental stakes of the supply chain*

194 As explained in the introduction, we study five environmental pressures that are especially relevant for the
 195 cereals supply chain: energy consumption, GHG emissions, land use, use of pesticides and blue water
 196 consumption. Berger and Finkbeiner (2013) show drawbacks of volumetric water footprints, arguing that
 197 numerically smaller footprints can cause higher impacts. In particular they criticize the aggregation of green
 198 and blue water footprints by questioning the definition of water consumption. In this work, we build on
 199 previous diagnosis about regional water stress, and study the blue water footprint of cereals, that is the with-
 200 drawals of surface or groundwater. Table 2 presents the data sources used for estimating pressures from the
 201 producer's viewpoint.

202

Extension of the AMC model to environmental pressures

Let α be the number of environmental pressures under study, 5 in our case. We define matrix F so that F_{ij} represents the direct emission of environmental pressure i by sector-region j . F_i is the total environmental pressure i emitted, whatever the sector or region. Finally, f matrix is defined as: $f_{ij} = F_{ij}/F_i$. We then extend our Q and R matrices as follow, in line with Duchin and Levine (2010):

$$Q' = \begin{matrix} & \alpha & dim_Q \\ \alpha & \begin{pmatrix} 0 & f \\ 0 & Q \end{pmatrix} \end{matrix} \quad R' = \begin{matrix} & dim_R \\ \alpha & \begin{pmatrix} 0 \\ R \end{pmatrix} \end{matrix} \quad Z' = \begin{matrix} & 1 \\ \alpha & \begin{pmatrix} F \\ Z \end{pmatrix} \end{matrix}$$

We compute matrices N' , B' the same way as explained above:

$$N' = \begin{matrix} & \alpha & dim_Q \\ \alpha & \begin{pmatrix} I & fN \\ 0 & N \end{pmatrix} \end{matrix} \quad B' = \begin{matrix} & dim_R \\ \alpha & \begin{pmatrix} fB \\ B \end{pmatrix} \end{matrix}$$

203 The i^{th} row of B' ($i \leq \alpha$) indicates in what consumption environmental pressure i is eventually embodied,
 204 summing all the paths taken from production to consumption. Similarly to IOA, it is however interesting to
 205 compute the main paths contributing to this sum, using the Taylor decomposition of matrix N' . We describe
 206 the algorithm used for this purpose in the Supplementary Material.

Pressure	Production	Transformation	Transport
Energy	Agribalyse, national average (ratio per kg of product)	Agreste survey on energy consumption in the agro-industry (regional data)	Base Carbone (ratio per t.km)
Greenhouse gases	Agribalyse, national average (ratio per kg of product)	Energy use times emission factors	Base Carbone (ratio per t.km)
Land use	Agreste (French regions), FAO (foreign countries)	-	-
Pesticides use	Agribalyse, national average (kg of active substance per ha), Agreste survey on farming practices (regional Treatment Frequency Indices)	-	-
Blue water footprint	Mekonnen and Hoekstra (2011), Ercin et al. (2012)	IREP database	-

Table 2: Datasources for pressure estimation from the producer’s viewpoint. The production stage refers to the production of raw materials (called extraction in the MFA terminology). Agribalyse (Ademe, 2015b) an official Life-Cycle-Inventory and Life-Cycle Assessment database for French agricultural products. Base carbone (Ademe, 2015a) is an official database for greenhouse gases emission factors. Agreste is the statistical service of the French Ministry of Agriculture. The IREP database (Ineris, 2015) provides water withdrawals of industrial sites that reach registration thresholds; extrapolations for each sector of the agro-industry were computed on this basis.

Results

In this section we present a range of questions than can be tackled with the model described above, stating each time what matrices are used. It is meant to be illustrative and therefore focuses on a few examples only. More comprehensive results are available in the Supplementary Material. The same methodology could be applied to other supply chains, territories and environmental pressures. We then discuss the limits of the model and some potential leads to improve it.

Studying the fate of a specific product

As explained before, the model is focused on France and its main goal is to track resources and pressures downstream. In order to illustrate this, we show the fate of corn grown in the Midi-Pyrénées region. This example is of particular interest because water is becoming a major stake in this region both in terms of quality (in particular, pollution by pesticides) and quantity. We use matrix B to produce the results. They indicate that nearly two thirds of the corn is embodied in the consumption of foreign countries, pointing to the internalization of environmental impacts in Midi-Pyrénées. Figure 1 shows the regions of destination. It is also interesting to study under what form the corn is eventually consumed. 49% remains under the form of grain, meaning it is exported, lost or used for seeds. Animal products account for 48% of the total (43% for meat only, 4% for milk and 1% for eggs). Since the fate of exported grains is not modeled, this number is underestimated, given most of the exported corn is likely to be fed to livestock. Finally starch and canned corn respectively represent 2% and 1%.

Studying the supply area for a specific product

Another way to exploit the results is to estimate supply areas for specific products. Starting from a final

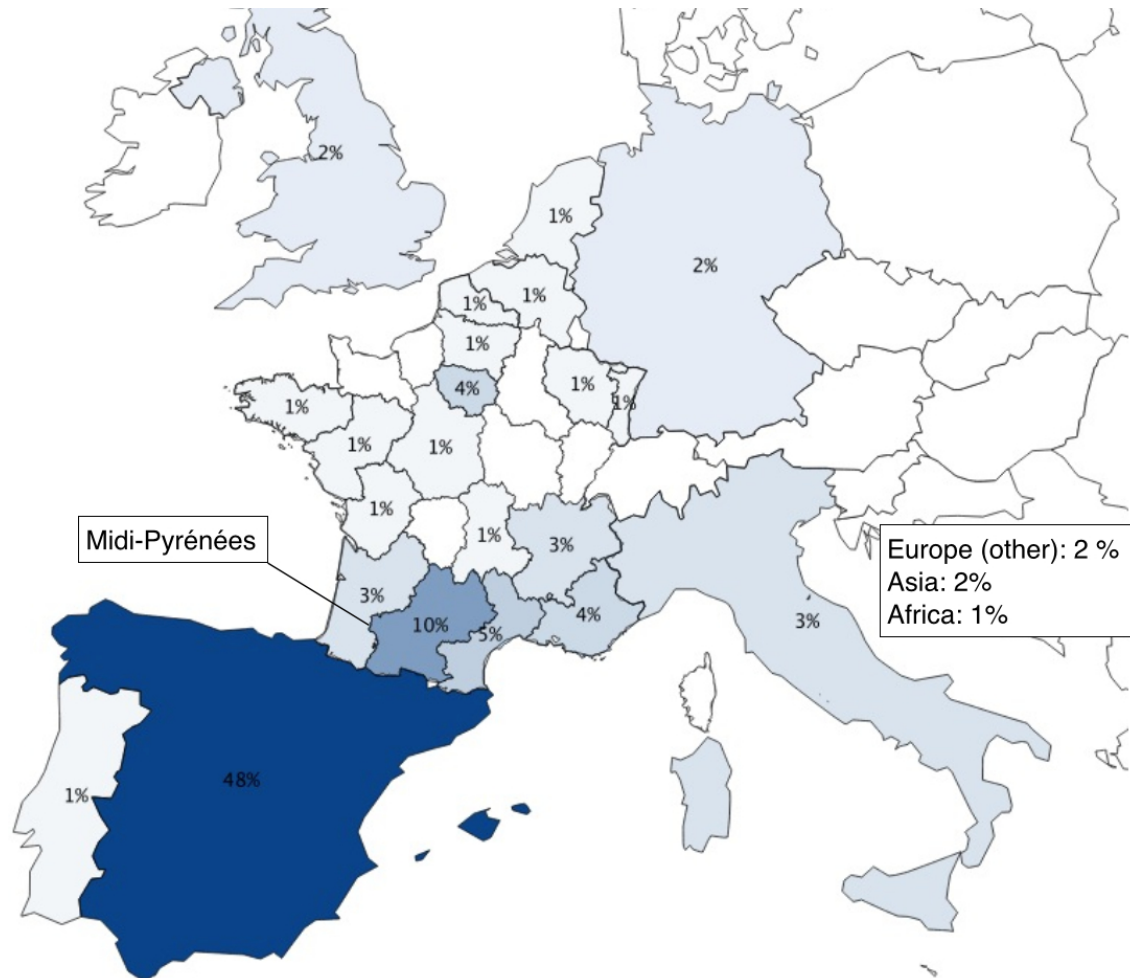


Figure 1: Fate of corn grown in the Midi-Pyrénées region. Darker color means greater consumption of corn or corn products. With nearly half of the regional production, Spain is by far the main destination. Additional cross-check with FAO statistics shows that Spain only exports about 1% of its corn supply. 10% of the production of corn in Midi-Pyrénées eventually serves local consumption, mostly under the form of meat (7%), seeds and losses and milk products accounting respectively for 2% and 1%.

229 product, it is interesting to trace back earlier production stages and to compute average supply distances
 230 at each stage. This gives an idea of the degree of dependency of the region regarding the consumption of
 231 this final product. To illustrate this, we use matrix L along with distances matrices to analyze the supply of
 232 bread in the Provence-Alpes-Côte-d'Azur region (PACA). Figure 2 shows that the more we go back in the
 233 supply chain the further supply areas are located: average supply distances for bread, flour and wheat are
 234 respectively 55 km, 195 km and 470 km (distance is considered null for products originating from the PACA
 235 region itself).

236

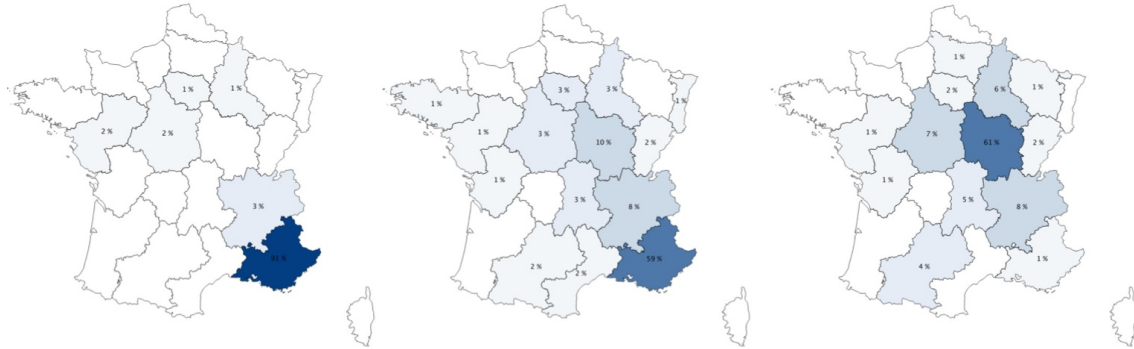


Figure 2: The supply chain of bread consumed in the Provence-Alpes-Côte-d'Azur (PACA) region. From left to right: supply areas for bread, flour used for bread and wheat used for bread. Darker color means greater contribution. Supply coming from abroad is negligible (less than 1% in each case).

237 *Identifying the main life-cycle-steps producing environmental pressures*

238 Table 3 shows total amounts of pressures produced (whatever the region of production) and splits them
 239 among the production, transformation and transport phases using matrix $\hat{F}f$. In all cases, the production
 240 phase clearly stands out as the most critical. Still, in the case of GHG, transformation and transport are
 241 significant with nearly one third of total emissions. Regarding the transport sector, road freight ranks first
 242 as GHG emitter (79% of the emissions with 28% of the tonnes kilometers), followed by sea freight (19% of
 243 the emissions with 66% of the tonnes kilometers). Domestic transport only represents 16% of total tonnes
 244 kilometers although it amounts to 64% of the tonnage traded. The production phase represents a larger part
 245 in energy consumption than in GHG emissions because of a biomass-based energy consumption at the farm,
 246 according to the LCA database. Regarding the blue water footprint of transformation industries, starch factories
 247 rank first with about two thirds of the water consumption⁵.

248

249 *Studying the needs associated to a specific consumption*

250 Matrix L is used to compute productions needed in every region to satisfy the consumption of a specific
 251 product in a specific region. We illustrate this with the example of French meat consumed in Italy⁶, Italy
 252 being the first trade partner of France for this product. Table 4 presents the results. The order of magnitude
 253 of GHG emissions per kg seems a bit low compared to other LCA results⁷. Indeed, results here only encom-
 254 pass the portion of the emissions linked to the cereals supply chain (emissions from livestock digestion are
 255 for instance excluded). 4 m² were used to grow 2.8 kg of cereals needed to feed the livestock⁸, in particular
 256 in the Centre region (for 14%). 13800 kcal are embodied in 1 kg of meat; by comparison, the caloric value
 257 of this kg of meat is about 2000 kcal. We compared pressures associated with Italian consumption with other

Pressure	Production	Transformation	Transport	Total
Energy use	86 %	5 %	9 %	407 TWh
GHG emissions	68 %	8 %	24 %	42.0 Mt CO ₂ eq.
Land use	100 %	-	-	10.3 Mha
Pesticides use	100 %	-	-	20.0 kt
Blue water footprint	96 %	4 %	-	2.58 Gm ³

Table 3: Contribution of each life-cycle stage to the environmental pressures under study. Pesticides use are expressed in weight of active substance.

258 regions and saw that indices do not vary a lot (generally more or less 10%) except for the ones related to blue
 259 water footprint and transport. This is explained by the fact that the production phase is the most significant
 260 one, as we saw above. The difference in blue water footprint intensities can be explained by the variability
 261 in cereal mix fed to livestock (corn being a lot more water-intensive than wheat).

262

Topic	Quantities associated to 1 kg of meat
Energy	16 kWh
GHG	1.6 kg CO ₂ eq.
Land use	4.0 m ²
Pesticides use	0.75 g (of active substance)
Blue water footprint	130 L
Sea freight	0.6 t.km
Road freight	2.0 t.km
Rail and river freight	0.2 t.km

Table 4: Environmental pressures and transport associated with the consumption of 1 kg of meat from France in Italy.

263 *Identifying the main paths linking production to consumption*

264 We use a structural path analysis (SPA) algorithm, inspired by Peters and Hertwich (2006b), on matrix B
 265 in order to extract the main links between production of environmental pressures and final consumption of
 266 products. The algorithm is described in Supplementary Material. Table 5 presents the top five paths linked
 267 to GHG emissions as well as three other paths illustrating different emission patterns. The first 30 paths are
 268 linked to exports and contribute to nearly 10% of total GHG emissions of the supply chain. The largest path
 269 for freight emission is the one representing exports of corn from Aquitaine to Spain by road. The path of
 270 emissions due to the growing of wheat in Bretagne, to feed animals for meat consumption in Ile-de-France,
 271 is the main emission path related to French consumption. Finally the main path related to pressures occur-
 272 ring during the transformation step is the emission of craft bakeries in Ile-de-France for local consumption.
 273 The first 100 paths (listed in Supplementary Material) account for 17% of total emissions.

274

275 *Building environmental accounts from the producer's and from the consumer's perspective*

276 For each region, we can build environmental accounts from the producer's (what is emitted/used by the pro-
 277 ductive activity of the region) and consumer's (what is emitted/used to satisfy the final consumption of the
 278 region) perspectives. For this purpose we respectively use matrices $\hat{F}f$ and $\hat{F}fB$. Table 6 shows the top ten
 279 regions in both perspectives regarding the land use footprint. This can be seen as an Ecological Footprint

Rank	Path	Contribution
1	Growing of wheat in Picardie > Consumption of wheat in Belgium	5.6 ‰
2	Growing of wheat in Picardie > Consumption of wheat in the Netherlands	5.6 ‰
3	Growing of corn in Aquitaine > Consumption of corn in Spain	4.9 ‰
4	Road freight from Aquitaine to Spain > Consumption of corn in Spain	4.5 ‰
5	Growing of wheat in Haute-Normandie > Consumption of wheat in Algeria	4.2 ‰
...
31	Growing of wheat in Bretagne > Making of compound feed in Bretagne > Animal farming in Bretagne > Consumption of meat in Ile-de-France	1.8 ‰
...
44	Production of bread in craft bakery in Ile-de-France > Consumption of bread in Ile-de-France	1.4 ‰

Table 5: Paths from emissions of GHG to final consumption. The column *contribution* shows the portion of total GHG emissions explained by each path. Picardie, Aquitaine, Haute-Normandie, Bretagne are French regions, Ile-de-France is the Parisian region (with the largest population).

280 of cropland from the production and consumption perspectives (Wackernagel et al., 2005), although results
 281 are presented in real surface and not in surface of average bioproductive land. Similar accounts can be built
 282 for all the pressures under study: rankings vary little except for the case of the blue water footprint, which is
 283 mostly driven by corn production and consumption.

284

Region	Land use footprint of production	Region	Land use footprint of consumption
Centre (FR)	1250 kha (12%)	Ile-de-France (FR)	834 kha (8%)
Poitou-Charentes (FR)	720 kha (7%)	Italy	741 kha (7%)
Champagne-Ardenne (FR)	719 kha (7%)	Spain	656 kha (6%)
Midi-Pyrénées (FR)	702 kha (7%)	The Netherlands	627 kha (6%)
Picardie (FR)	689 kha (7%)	Belgium	588 kha (6%)

Table 6: Land use footprint (real surface) from the producer's and from the consumer's perspectives. Only the top five regions are displayed. Of course, the total land use footprint of production is equal to the total land use footprint of consumption.

285 *Comparing environmental efficiency of different regions' consumptions*

286 Knowing the population of each region, we can then estimate per-capita consumption footprints: detailed
 287 results are available in Supplementary Material. On average the French per-capita footprint linked to the
 288 cereals supply chain is about 3.1 MWh, 0.33 t CO₂ eq., 780 m², 0.15 kg of active substance of pesticides and
 289 20 m³ of blue water. The two main French regions in terms of population are Ile-de-France and Rhône-Alpes
 290 (with respectively about 11.6 millions and 6.1 millions inhabitants in 2007). Looking at these two regions,
 291 per capita footprints are the same in the case of GHG emissions and the maximum difference is obtained in
 292 the case of blue water with 12%. Given the differences may be in the range of the model's uncertainties, it
 293 would be premature to draw precise conclusions based on these results. However, they show French regions
 294 have relatively homogeneous footprints of consumption.

295

296 *Limits of the model and perspectives of improvement*

297 In this section, we discuss the limits of the model and some leads for future developments.

- 298 • The model is limited to the study of the cereals supply chain. For instance, soy cakes fed to livestock
299 are not taken into account because they are oleaginous. Two levels of improvement can be targeted
300 in the future to overcome this limitation. The first one is to apply the methodology on all the main
301 agri-food supply chains (oleaginous, sugar, wine, fruits and vegetables, animal breeding) in order to
302 have a comprehensive view on the food issue. The second one would be to extend the model to the
303 main industrial supply chains (such as energy, wood, concrete, steel and chemistry). The obtention of
304 such physical, highly disaggregated supply/use table is of course a longer-term project.
- 305 • The model is focused on France. Foreign countries are only considered for their role of outlet or
306 provider and their interior supply chain is not fully depicted; nor is trade between them. Including each
307 country/continent's supply chain would be useful to track downstream flows to their final destination,
308 although *a priori* it wouldn't be possible to reach the same level of disaggregation as in the case of
309 France. FAO statistics could be used to implement this idea.
- 310 • On a similar topic, the model could be compared and enriched with the works of Kastner et al. (2011)
311 and Godar et al. (2015) that depict methods for enhanced tracing of international trade and subnational
312 footprints.
- 313 • Intra-regional freight is not taken into account because of a lack of information: the distance between
314 local crop fields and transformation industries in the same region is neglected, only inter-regional
315 and international distances are estimated. The fact that French regions have developed specialization
316 strategies, consequently relying a lot on inter-regional trade, makes it less problematic.
- 317 • Transport of consumers to local shops or to supermarkets is not considered. Rather than a technical
318 impossibility, it was left out of the model because the authors did not find useful for policy-making to
319 study the part of the travel to the supermarket that should be allocated to cereal products. It is however
320 an important question once the scope of the study widens to the full basket of a household.
- 321 • Currently, part of the pressures related to inputs at the farm are not traced back to their geographi-
322 cal origin since LCA results are directly applied. This is for instance the case for GHG emissions
323 occurring during the production of fertilizers, which may be located elsewhere.
- 324 • Uncertainties associated with MFA results were previously estimated. Adding confidence intervals to
325 environmental pressure ratios would make it possible to compute interval of confidence of the model's
326 outputs which would be useful for a better interpretation of the results. Work is underway to estimate
327 the missing intervals of confidence.

328 **Conclusion**

329 The goal of this article was to show the potentialities of coupling supply chain MFA with AMC and envi-
330 ronmental pressures. Adopting a downstream perspective through the use of AMC seems well-adapted to
331 exporting regions. The implementation of the methodology on the case of French cereals leads to interesting
332 results that could serve as a starting point for decision-aiding. The supply chain object is well adapted to
333 understand what life-cycle stages (production, transformation, transport) are predominant regarding each
334 environmental pressure: regarding GHG, it appears for instance that the transport of goods, mostly through

335 road freight, is not negligible, which raises the question of fostering rail and river transport between French
336 regions and between France and its direct neighbors. Given the relatively small variability of cultural prac-
337 tices in France, land use appears to be a good proxy of other pressures such as the use of pesticides. On the
338 contrary, the blue water footprint is driven by corn production and therefore concentrates on specific regions.
339 While previous studies have pointed out the major responsibility of corn production regarding water scarcity
340 in these regions (Ercin et al., 2012), the analysis of the fate of corn production leads to two lines of thoughts.
341 First, consumption of animal products is by far the main driver of production, and prospective scenarios of
342 dietary changes should therefore be examined. Second, Spain appears as the main importer of French corn
343 and consequently externalizes the associated pressures on the local environment: in particular qualitative and
344 quantitative stresses put on water resources through the use of pesticides and irrigation. This situation points
345 to a limit of the study: only one supply chain was taken into account so we lack information on “net trade of
346 pressures” all activities considered. For instance, in return, France imports a lot of fruits and vegetables from
347 Spain, grown in regions with even greater water-scarcity. Hence, a comprehensive view with a multi-supply
348 chains approach is needed in order to be more policy-relevant. Linking this study with recent works on Spanish
349 agri-food industries and multi-regional input-output tables is a promising perspective (Cazcarro et al., 2013,
350 2014).

351 The choice of a subnational spatial resolution was motivated by the existence of leverages of regional
352 administrative levels but also by the potentialities it opens to analyze impacts of specialization strategies or
353 to compare environmental efficiencies of regional consumptions. Given the model’s uncertainties, results are
354 not conclusive regarding inter-regional comparison of efficiencies except for the specific aspect of transport
355 for which we observe a large variability of regional profiles. On the contrary, results are useful for the
356 environmental evaluation of regional strategies, starting with the diagnosis. The level of detail of the model
357 provides a concrete picture of each territory, all the more so as a finer spatial resolution is achievable.
358 As stated in the introduction, the present work is part of a larger project aiming at the analysis of local
359 supply chains from the environmental, economic and social points of view for decision-aiding. In this
360 perspective the next step is to include socio-economical indicators (a minimum set of indicators being a labor
361 footprint and an index on added value) to the model and to evaluate possible alternatives of development.
362 Relevant areas of investigations related to cereals include the study of trade-offs of exports, adaptation to
363 climate change (given water scarcity is planned to worsen in regions that are already enduring water stress)
364 and trade-offs between food use and energy-use (for instance, bioethanol production has known a constant
365 increase in recent years). The Afterres scenario (Solagro, 2014) envisions the future of land use in France
366 in 2050 in concordance with the Negawatt scenario of energy transition (Négawatt, 2013). Changes in both
367 modes of production and in modes of consumption are proposed. On the consumption side, 3 actions are
368 implemented: reduction of protein intake (currently in surplus), reduction of food waste and reduction of
369 the proportion of animal proteins in the total intake. Concretely this translates into more direct cereal intake
370 but eventually less cereals need for food purposes. On the production side, the scenario suggests a 50%
371 proportion of organic agriculture by 2050, a division of corn export by two because of water stress and a
372 partial re-affectation of arable land (mostly prairies) freed from animal production towards energy production.
373 The work of regionalization of this scenario is in progress and it will eventually be useful for regional and
374 national decision-makers to be able to compare this vision of the future with a business as usual scenario.
375 The model and leads of development presented here are an important step towards this goal.

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Notes

- ¹IO tables are not compiled at the level of French regions and the national table only distinguishes between 65 sectors.
- ²This number includes livestock and crop farming (most of the emissions accounted for occur under the form of methane and nitrogen protoxide).
- ³We deliberately name this matrix L because it can be seen as an equivalent of the traditional Leontief matrix in IOA.
- ⁴Elements equal to zero in vector C are replaced by ones in order to make \hat{C} invertible ; the same is done on Z' vectors. This operation is purely technical and has no impact on the results.
- ⁵Starch but also bioethanol, beer and canned corn factories were identified as major water consumers per unit of production.
- ⁶More precisely the meat considered here originates from the meat supply of France (both national production and imports).
- ⁷For instance emissions factor for cattle, pork and chicken meats are respectively 12, 2.3 and 2.2 kg CO₂ eq. per kg according to Ademe (2015b).
- ⁸This does not include soy feed as explained in the discussion. Given national use of soy cakes for livestock consumption, the order of magnitude is 1 kg of soy per kg of meat (expressed in carcassee-weight equivalent), most of this soy originating from Brazil and Argentina.

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