Environmental Pressures Embodied in the French Cereals Supply Chain

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

Environmental pressures embodied in the French cereals supply chain

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

Abstract

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

Introduction

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

Life Cycle Assessment (LCA), or more simply with ratios of pressure intensity (Rochat et al., 2013). This is for instance the approach followed in the classical calculation of the Ecological Footprint (Wackernagel et al., 2005). Each method having its own drawbacks (typically, trade of services is not accounted for in the MFA-based approach, while IOA can sometimes lead to questionable results (Kastner et al., 2014)), the choice between the two relies on the research question and on data availability. Our study is based on supply chain material flows because of our focus on the regional level and of the level of detail we aim at[1].

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

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

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

We study five environmental pressures that are especially relevant for the cereals supply chain: energy consumption, GHG emissions, land use, use of pesticides and blue water consumption. Both global (for instance GHG emissions) and local (for instance use of pesticides) environmental pressures were included in order to aim at a holistic view of the situation. A recent assessment of the implementation of the Water Framework Directive in France revealed that rivers' contamination with pesticides was especially high in cereals-growing regions (SOeS, 2015a). With about 90 Mt CO_2 eq., agriculture is responsible for nearly one fifth of French greenhouse gazes emissions[2] (SOeS, 2015b). Tranport and of transformation industries are also responsible for emissions through their use of energy. According to Ercin et al. (2012), crop growing accounts for half of the French blue water footprint of production. Cereals represent 59% of this half, corn representing 50% on its own (the last 9% are shared between rice, wheat, triticale, barley and oats). Production of corn ranks first in the causes of water scarcity in the summer months in many regions, especially in Midi-Pyrénées, Aquitaine, Poitou-Charentes and Centre.

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

Materials and methods

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

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

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

An MFA on cereals in every French region

We base the model on previous results of the authors (Courtonne et al., 2015). MFAs on the cereals supply chain in the 22 French regions were produced in the form of reconciled physical supply and use tables by downscaling the national MFA. 19 products (raw materials, intermediate and end-products) and 18 industries were taken into account. The period studied was the annual average between years 2001 and 2009 and is therefore the same in the present article.
In this previous work, theses MFAs were limited to physical cereal flows, for instance flows of bread were considered because they physically embody cereal grains but flows of livestock products were left out, meaning that the model considered livestock consumption as a final consumption. This makes sense in a pure MFA study but becomes problematic when one is interested in studying and allocating environmental pressures: typically, husbandry regions would then have a high consumption footprint even if their animal products are consumed elsewhere.

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

An AMC model to track flows from producers to consumers

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

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

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

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

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

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

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

Vectors Z^r are composed of 3 parts:

$$Z^r = \begin{matrix} q \\ p \\ t \end{matrix} \overset{1}{\begin{pmatrix} Z^r_1 \\ Z^r_2 \\ Z^r_3 \end{pmatrix}} \qquad Z^r_1 = \left[\overline{(S^r)^T}\right] \qquad Z^r_2 = \left[\overline{S^r} + \textstyle\sum_s E^{s,r}\right] = \left[\overline{U^r} + \textstyle\sum_s E^{r,s} + C^r\right] \qquad Z^r_3 = \left[\overline{T^r}\right]$$

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

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

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

$$D^{r,s} = D^{s,r} \qquad D^{r,s}_{m,j} = D^{r,s}_{m,k} \quad \forall\ products\ j,\ k \tag{2}$$

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:

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

with

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

and

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

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

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

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

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

Each row i of matrix B can be interpreted as the fate of sector/product i. For instance, the B_{ij} term is the proportion of i that is finally embodied in region-product j. As we will show it in the next section, it is interesting to aggregate the terms either by product type or by region. If we define the Z vector as equation 4, we can compute matrix $\hat{Z}B$, with the ij^{th} term representing the amount of i finally embodied in region-product j. Finally, we can compute matrix L[3] as defined in equation 5[4] and its ij^{th} term will be interpreted as the amount of i needed in order to consume one unit of region-product j.

$$Z = \begin{bmatrix} Z^1 \\ \vdots \\ Z^n \end{bmatrix} \tag{4}$$

$$L = \hat{Z}\, B\, \hat{C}^{-1} \qquad with\ \ C = \begin{bmatrix} C^1 \\ \vdots \\ C^n \end{bmatrix} \tag{5}$$

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.

Coupling material flows with environmental pressures

Data sources to inform environmental stakes of the supply chain

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

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):

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

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

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

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

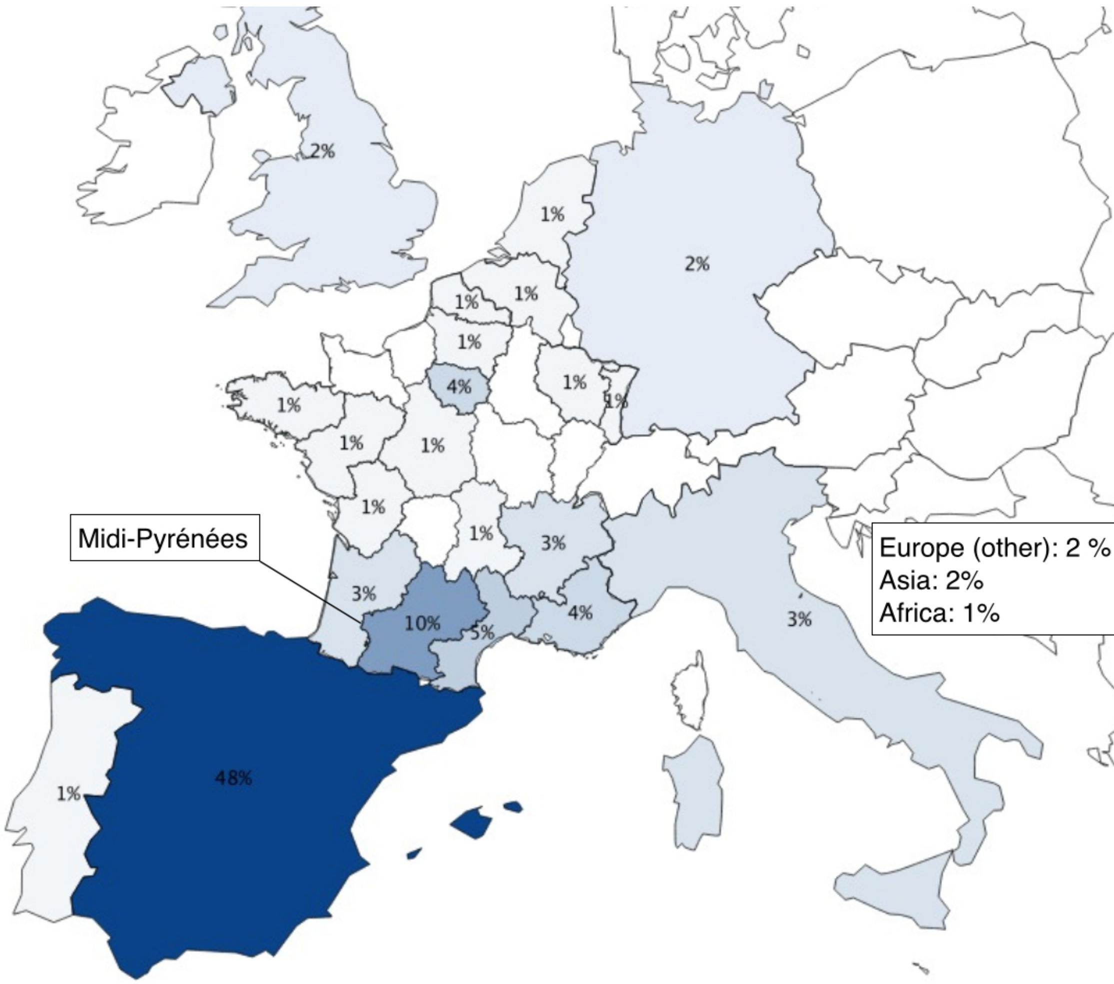

Figure 1: Fate of corn grown in the Midi-Pyrénées region. Darker color means greater consumption of corn or corn products. With nearly half of the regional production, Spain is by far the main destination. Additional cross-check with FAO statistics shows that Spain only exports about 1% of its corn supply. 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%.

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

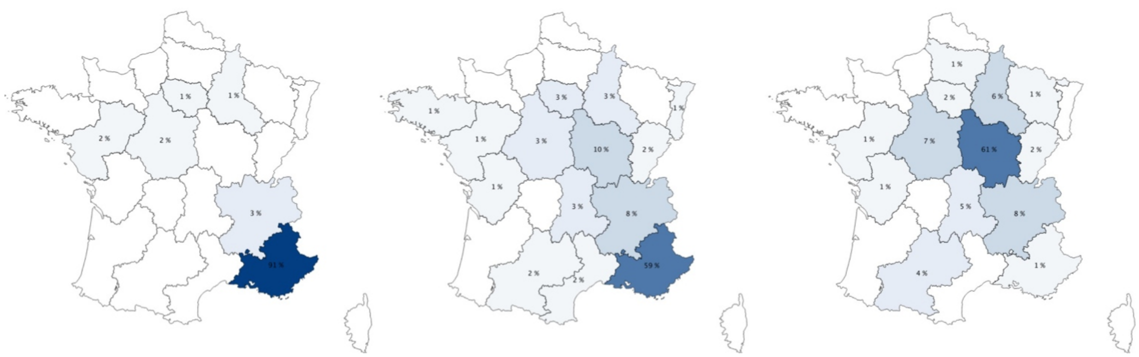

Figure 2: The supply chain of bread consumed in the Provence-Alpes-Côte-d'Azur (PACA) region. From left to right: supply areas for bread, flour used for bread and wheat used for bread. Darker color means greater contribution. Supply coming from abroad is negligible (less than 1% in each case).

Identifying the main life-cycle-steps producing environmental pressures

Table 3 shows total amounts of pressures produced (whatever the region of production) and splits them among the production, transformation and transport phases using matrix $\hat{F}f$. In all cases, the production phase clearly stands out as the most critical. Still, in the case of GHG, transformation and transport are significant with nearly one third of total emissions. Regarding the transport sector, road freight ranks first as GHG emitter (79% of the emissions with 28% of the tonnes kilometers), followed by sea freight (19% of the emissions with 66% of the tonnes kilometers). Domestic transport only represents 16% of total tonnes kilometers although it amounts to 64% of the tonnage traded. The production phase represents a larger part in energy consumption than in GHG emissions because of a biomass-based energy consumption at the farm, according to the LCA database. Regarding the blue water footprint of transformation industries, starch factories rank first with about two thirds of the water consumption[5].

Studying the needs associated to a specific consumption

Matrix L is used to compute productions needed in every region to satisfy the consumption of a specific product in a specific region. We illustrate this with the example of French meat consumed in Italy[6], Italy being the first trade partner of France for this product. Table 4 presents the results. The order of magnitude of GHG emissions per kg seems a bit low compared to other LCA results[7]. Indeed, results here only encompass the portion of the emissions linked to the cereals supply chain (emissions from livestock digestion are for instance excluded). 4 m^2 were used to grow 2.8 kg of cereals needed to feed the livestock[8], in particular in the Centre region (for 14%). 13800 kcal are embodied in 1 kg of meat; by comparison, the caloric value 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.

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

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.

Identifying the main paths linking production to consumption

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

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

For each region, we can build environmental accounts from the producer's (what is emitted/used by the productive activity of the region) and consumer's (what is emitted/used to satisfy the final consumption of the region) perspectives. For this purpose we respectively use matrices $\hat{F}f$ and $\hat{F}fB$. Table 6 shows the top ten 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).

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

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.

Comparing environmental efficiency of different regions' consumptions

Knowing the population of each region, we can then estimate per-capita consumption footprints: detailed results are available in Supplementary Material. On average the French per-capita footprint linked to the cereals supply chain is about 3.1 MWh, 0.33 t CO_2 eq., 780 m^2, 0.15 kg of active substance of pesticides and 20 m^3 of blue water. The two main French regions in terms of population are Ile-de-France and Rhône-Alpes (with respectively about 11.6 millions and 6.1 millions inhabitants in 2007). Looking at these two regions, per capita footprints are the same in the case of GHG emissions and the maximum difference is obtained in the case of blue water with 12%. Given the differences may be in the range of the model's uncertainties, it would be premature to draw precise conclusions based on these results. However, they show French regions have relatively homogeneous footprints of consumption.

Limits of the model and perspectives of improvement

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

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

Conclusion

The goal of this article was to show the potentialities of coupling supply chain MFA with AMC and environmental pressures. Adopting a downstream perspective through the use of AMC seems well-adapted to exporting regions. The implementation of the methodology on the case of French cereals leads to interesting results that could serve as a starting point for decision-aiding. The supply chain object is well adapted to understand what life-cycle stages (production, transformation, transport) are predominant regarding each environmental pressure: regarding GHG, it appears for instance that the transport of goods, mostly through road freight, is not negligible, which raises the question of fostering rail and river transport between French regions and between France and its direct neighbors. Given the relatively small variability of cultural practices in France, land use appears to be a good proxy of other pressures such as the use of pesticides. On the contrary, the blue water footprint is driven by corn production and therefore concentrates on specific regions. While previous studies have pointed out the major responsibility of corn production regarding water scarcity in these regions (Ercin et al., 2012), the analysis of the fate of corn production leads to two lines of thoughts. First, consumption of animal products is by far the main driver of production, and prospective scenarios of dietary changes should therefore be examined. Second, Spain appears as the main importer of French corn and consequently externalizes the associated pressures on the local environment: in particular qualitative and quantitative stresses put on water resources through the use of pesticides and irrigation. This situation points to a limit of the study: only one supply chain was taken into account so we lack information on "net trade of pressures" all activities considered. For instance, in return, France imports a lot of fruits and vegetables from Spain, grown in regions with even greater water-scarcity. Hence, a comprehensive view with a multi-supply chains approach is needed in order be more policy-relevant. Linking this study with recent works on Spanish agri-food industries and mutli-regional input-output tables is a promising perspective (Cazcarro et al., 2013, 2014).

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

Acknowledgments

This research was funded by grants from Inria and Artelia Eau & Environnement.

Notes

[1]IO tables are not compiled at the level of French regions and the national table only distinguishes between 65 sectors.

[2]This number includes livestock and crop farming (most of the emissions acounted for occur under the form of methane and nitrogen protoxide).

[3]We deliberately name this matrix *L* because it can be seen as an equivalent of the traditional Leontief matrix in IOA.

[4]Elements equal to zero in vector C are replaced by ones in order to make $\hat{C}$ inversible ; the same is done on Z^r vectors. This operation is purely technical and has no impact on the results.

[5]Starch but also bioethanol, beer and canned corn factories were identified as major water consumers per unit of production.

[6]More precisely the meat considered here originates from the meat supply of France (both national production and imports).

[7]For instance emissions factor for cattle, pork and chicken meats are respectively 12, 2.3 and 2.2 kg CO_2 eq. per kg according to Ademe (2015b).

[8]This does not include soy feed as explained in the discussion. Given national use of soycakes for livestock consumption, the order of magnitude is 1 kg of soy per kg of meat (expressed in carcasse-weight equivalent), most of this soy originating from Brazil and Argentina.

References

Ademe (2015a). Base carbone. *http://bilans-ges.ademe.fr/fr/basecarbone/donnees-consulter*.

Ademe (2015b). L'outil agribalyse. *http://www.ademe.fr/expertises/produire-autrement/production-agricole/passer-a-laction/dossier/levaluation-environnementale-agriculture/loutil-agribalyse-agribalyse-program*.

Berger, M. and M. Finkbeiner (2013). Methodological challenges in volumetric and impact-oriented water footprints. *Journal of Industrial Ecology 17*(1), 79–89.

Bruckner, M., S. Giljum, C. Lutz, and K. Svenja Wiebe (2012). Materials embodied in international trade: Global material extraction and consumption between 1995 and 2005. *Global Environmental Change 22*(3), 568 – 576.

Calame, P. and A. Lalucq (2009). *Essai sur l'œconomie*. Charles Léopold Mayer.

Cazcarro, I., R. Duarte, and J. S. Chóliz (2013). Multiregional input?output model for the evaluation of spanish water flows. *Environmental Science & Technology 47*(21), 12275–12283.

Cazcarro, I., R. Duarte, J. Sánchez-Chóliz, C. Sarasa, and A. Serrano (2014). Environmental footprints and scenario analysis for assessing the impacts of the agri-food industry on a regional economy. *Journal of Industrial Ecology* (online preview).

Courtonne, J.-Y., J. Alapetite, P.-Y. Longaretti, D. Dupré, and E. Prados (2015). Downscaling material flow analysis: The case of the cereal supply chain in france. *Ecological Economics 118*, 67 – 80.

Duchin, F. and S. H. Levine (2010). Embodied resource flows and product flows. *Journal of Industrial Ecology 14*(4), 586–597.

Duchin, F. and S. H. Levine (2013). Embodied resource flows in a global economy. *Journal of Industrial Ecology 17*(1), 65–78.

Eckelman, M. J. and I. Daigo (2008). Markov chain modeling of the global technological lifetime of copper. *Ecological Economics 67*(2), 265–273.

Eckelman, M. J., B. K. Reck, and T. E. Graedel (2012, June). Exploring the global journey of nickel with markov chain models. *Journal of Industrial Ecology 16*(3), 334–342.

Ercin, A. E., M. M. Mekonnen, and A. Y. Hoekstra (2012). The water footprint of france. *http://www.waterfootprint.org/Reports/Report56-WaterFootprintFrance.pdf*.

FranceAgriMer (2012). Panorama des échanges extérieurs du secteur agroalimentaire en 2011. *http://www.franceagrimer.fr/content/download/ 13153/94179/file/2012echanges-exterieursweb.pdf*.

Godar, J., U. M. Persson, E. J. Tizado, and P. Meyfroidt (2015). Towards more accurate and policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption. *Ecological Economics 112*, 25 – 35.

Guan, D. and K. Hubacek (2007). Assessment of regional trade and virtual water flows in china. *Ecological Economics 61*(1), 159 – 170.

Ineris (2015). Registre français des émissions polluantes (irep). *http://www.irep.ecologie.gouv.fr/IREP/index.php*.

Kastner, T., M. Kastner, and S. Nonhebel (2011). Tracing distant environmental impacts of agricultural products from a consumer perspective. *Ecological Economics 70*(6), 1032 – 1040.

Kastner, T., A. Schaffartzik, N. Eisenmenger, K.-H. Erb, H. Haberl, and F. Krausmann (2014). Cropland area embodied in international trade: Contradictory results from different approaches. *Ecological Economics 104*(0), 140 – 144.

Kemeny, J. and J. Snell (1976). *Finite Markov chains*. New-York, NY, USA: Springer-Verlag.

Leigh, M. and X. Li (2014). Industrial ecology, industrial symbiosis and supply chain environmental sustainability: a case study of a large UK distributor. *Journal of Cleaner Production* (online preview).

Lenzen, M., J. Murray, F. Sack, and T. Wiedmann (2007). Shared producer and consumer responsibility ? theory and practice. *Ecological Economics 61*(1), 27 – 42.

Mekonnen, M. M. and A. Y. Hoekstra (2011, May). The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci. 15*(5), 1577–1600.

Négawatt (2013). scénario négaWatt 2011 - dossier de synthèse. *www.negawatt.org/telechargement/SnW11//Scenario-negaWatt-2011_Dossier-de-synthese.pdf*.

Peters, G. P. and E. G. Hertwich (2006a). Pollution embodied in trade: The Norwegian case. *Global Environmental Change 16*(4), 379–387.

Peters, G. P. and E. G. Hertwich (2006b). Structural analysis of international trade: Environmental impacts of Norway. *Economic Systems Research 18*(2), 155–181.

Rochat, D., C. R. Binder, J. Diaz, and O. Jolliet (2013, October). Combining material flow analysis, life cycle assessment, and multiattribute utility theory. *Journal of Industrial Ecology 17*(5), 642–655.

Simas, M., R. Wood, and E. Hertwich (2014). Labor embodied in trade. *Journal of Industrial Ecology* (online preview).

SOeS (2015a). Contamination globale des cours d'eau par les pesticides. *http://www.statistiques.developpement-durable.gouv.fr/lessentiel/ar/246/211/contamination-globale-cours-deau-pesticides.html*.

SOeS (2015b). Repères - chiffres clés du climat France et Monde. *http://www.statistiques.developpement-durable.gouv.fr/fileadmin/documents/Produits_editoriaux/Publications/Reperes/2014/reperes-cc-climat-france-monde-ed-2015.pdf*.

Solagro (2014). Un scénario soutenable pour l'agriculture et l'utilisation des terres en France à l?horizon 2050. *http://www.solagro.org/site/393.html*.

Wackernagel, M., C. Monfreda, D. Moran, P. Wermer, S. Goldfinger, D. Deumling, and M. Murray (2005). National footprint and biocapacity accounts 2005 - the underlying calculation method. *Global Footprint Network, Oakland, CA*.

Wiedmann, T., R. Wood, J. C. Minx, M. Lenzen, D. Guan, and R. Harris (2010). A carbon footprint time series of the UK - results from a multi-region input-output model. *Economic systems research 22*(1), 19–42.

Yu, Y., K. Feng, and K. Hubacek (2013). Tele-connecting local consumption to global land use. *Global Environmental Change 23*(5), 1178 – 1186.

About the Authors

Jean-Yves Courtonne is PhD student in the STEEP team of INRIA, Grenoble, France. He is working under the joint supervision of Pierre-Yves Longaretti and Denis Dupré. Pierre-Yves Longaretti is CNRS researcher at IPAG, Joseph Fourier University, Grenoble, France and also member of the STEEP team INRIA. Denis Dupré is professeur at CERAG, Pierre Mendes-France University, Grenoble, France and has recently joined the STEEP team. Julien Alapetite is a research engineer working part-time with the STEEP team.

Corresponding Author

Jean-Yves Courtonne, INRIA, 655 Avenue de l'Europe, 38033, Montbonnot Saint-Martin, France; email: jean-yves.courtonne@inria.fr