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Reconstructing production efficiency, land use and trade for livestock systems in historical perspective. The case of France, 1961–2010

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Highlights

- Differential energy efficiency increase per livestock category from 1961 to 2010.
- Livestock production went 53 % up and land use 28% down in fifty years.
- Drop by 20 % of the share of pastures in total feed land in fifty years.
- Total virtual land trade is today about five times higher than the net land exports

Abstract

This paper provides an original accounting of changes in livestock production efficiency per livestock category in historical perspective and connects livestock consumption with land requirements and virtual land trade. We use France as a demonstration study and account for productivity changes in terms of energy. Feed rations composition are reconstructed per livestock product and feed crop group over time to account for changes in land use in relation to dietary changes. Land requirements for consumption in France dropped by 28% over the study period besides an increase by 35 % of population and by 53 % of livestock consumption. The two-fold increase in agricultural productivity is due, for half, to energy conversion efficiency improvements and for half to agricultural yields. Overall, the livestock energy conversion efficiency increased by 45% from 1961 to 2010, poultry gained 84%, pork 17%, sheep&goat 67 % and cattle 27%. The feed share of oilcrops and cereals in animal rations doubled against a drop by 35 % of feed from pastures. Virtual land imports for oilcrops in

relation to livestock consumption in France today amount to 0.9 million ha against a maximum of 1.9 million ha in 1979. Besides its dependence on oilcrops imports, the French livestock sector displays net virtual land exports ranging from about 2.5 to 5.3 million ha per year over the study period. Total virtual land trade is today five times higher than the net virtual trade. The difference highlights the share of circular product loops in increasingly integrated agricultural markets at the international scale.

Keywords: Energy conversion efficiency, livestock production, rations composition, land requirements, virtual land trade.

1. Introduction

Livestock production holds a central and growing role in agricultural production systems. Huge quantities of agricultural products go into animal feed. The total land area involved in livestock production has been estimated to about 70 % of all agricultural land, which is about 30 % of all ice-free terrestrial surface of the planet (Steinfeld, et al., 2006). Livestock production has the quasi-exclusive use of permanent grasslands and annual fodder crops and is the outlet of 36 % of global production of cereals and oilcrops (Herrero, et al., 2009; Alexandratos and Bruinsma, 2012). Over the past fifty years, the amount of crops used as feed has tripled (Davis & D'Odorico, 2015) in relation to dietary transitions towards higher consumption of livestock products especially in developing countries (Godfray, et al., 2010). According to the Food and Agricultural Organization (FAO), worldwide consumption of meat and dairy products are expected to further increase by respectively 76 % and 62 % by 2050 compared to the 2005/2007 levels (Alexandratos & Bruinsma, 2012). The projected increase outpaces demographic growth and will necessarily entail additional feed requirements and environmental pressure in relation to the production of these feed.

The livestock conversion efficiency of feed into food is a major underlying factor of resource requirements and environmental impacts of livestock consumption. Livestock impacts are of the same nature as impacts from crops but since feed to food conversion efficiency is inherently lower than one, the environmental pressure per unit of livestock product is always a multiple of the unitary pressure of the crops grown for feed. Accordingly, livestock is responsible for a major share of total environmental impacts of agriculture including land appropriation (i.e. Wirsenius et al. 2010; Kastner et al. 2012), consumption and pollution of water re-

sources (i.e. Hoekstra, 2012), alteration of biogeochemical cycles (i.e. Bouwman, et al, 2011), competition with biodiversity (i.e. Alkemade et al, 2010), climate change (i.e. Thornton, et al., 2009; Herrero, et al., 2013) and so on (Leip et al., 2015).

However, livestock conversion efficiency is not a time invariant and therefore resource use is itself a time dependent factor. In addition, the composition of animal rations, which is a major determinant of both livestock productivity and environmental impacts, is also subject to change in relation to crop systems transitions and international trade. Spatiotemporal variability in livestock systems and associated impacts are in part addressed in the scientific literature through life cycle assessments (i.e. de Vries and de Boer, 2009), nutritional requirements analysis (i.e Elferink and Nonhebel, 2006) and historical perspective analysis on specific time points (i.e. Bouwman et al. 2005; Chatzimpiros and Barles 2010). However, little is known on longer-term gradual conversion efficiency change and ranking among different livestock productions in relation to change in feed availability.

International feed trade is a major growing phenomenon over the past decades, largely driven by the industrialization of livestock sectors worldwide. It consists in the massive transfer of feed surpluses from world regions with specialized crop monocultures and little livestock to regions with footloose livestock operations (Naylor et al., 2005). It implies a growing global-scale integration of formerly locally mixed agricultural systems with implications in nutrient cycling, trade and losses (Lassaletta et al., 2014, 2016). For instance, South America is a notorious worldwide exporter of soybean feed, which export volumes increased by a factor of 35 between 1961 and 2013 (FAOSTAT, 2016). The physical flows of products give way to virtual flows of natural resources used in their production (Allan, 1998). Consequently, livestock systems depending on imported feed are increasingly dependent on virtual trade of land, water, nutrients and whatever other distant resource use in feed production (i.e. Galloway, et al., 2007; Würtenberger, et al., 2006; Burke, et al., 2008; Chatzimpiros and Barles, 2010, Qiang, et al. 2013, Lassaletta et al., 2016).

The paper focuses on changes in energy conversion efficiency (ECE) per livestock category in historical perspective based on a calculation approach using livestock production data (FAOSTAT 1961-2011). It also calculates aggregate nitrogen conversion efficiency (NCE) for all livestock to compare trends and to better connect to studies using nitrogen flows as a socio-environmental change indicator. It fills the gap of knowledge on long-term change of production efficiency. The approach is consumption-based and also connects livestock consumption to land requirements, keeping track of virtual land trade. Feed rations composition are reconstructed over time per livestock category and virtual land trade is assessed both in

terms of net and total trade. This provides a more complete picture of the trade activity and of the progressive integration of food systems at the international scale. We use France as a reference case but the approach is generic. France is Europe’s biggest agricultural producer with a dominant livestock sector within the EU27.

2. Methods and data

2.1. Overview of the approach

Land requirements are calculated for four distinct livestock categories: beef and milk, pork, poultry and sheep and goat. The four categories together represent more than 97% of livestock consumption in France. Figure 1 summarizes the calculation method for the reconstruction of historical energy and nitrogen conversion efficiencies (ECE, NCE) and land requirements for livestock consumption. The calculation is divided in the five main steps detailed below: i) aggregate ECE and NCE calculation ii) disaggregation of ECE per livestock sector iii) feed ration composition, iv) national feed and livestock trade balances v) land requirements calculation using agricultural yields and by-product allocation coefficients.

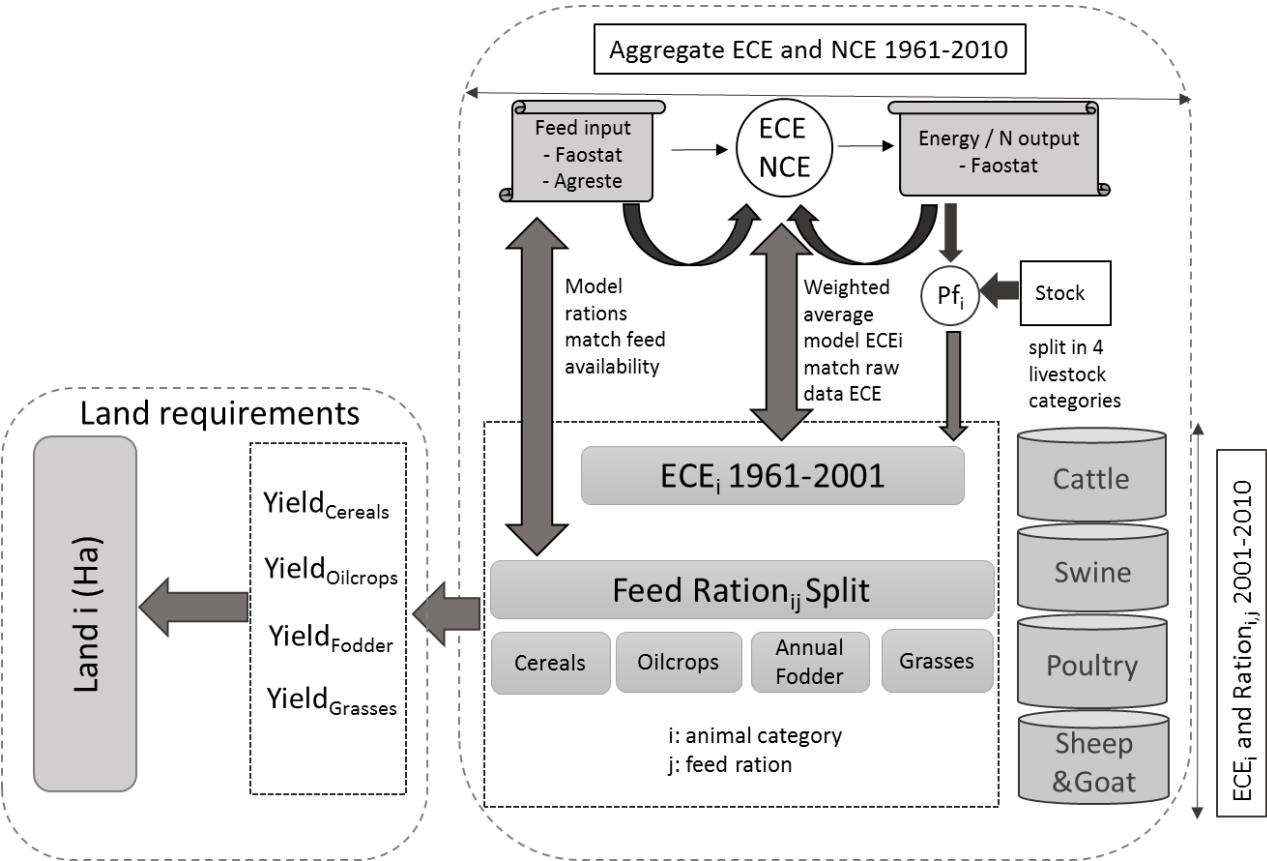


Figure 1: Calculation chart of livestock production efficiency and land requirements for consumption in France

2.2. Aggregate ECE of livestock in France

Energy conversion efficiency in livestock production is the ratio of output products to feed inputs both expressed as energy ($ECE = E_{output}/E_{input}$). Aggregate ECE for France is calculated since 1961 using FAOSTAT data, which report total annual feed inputs per crop (tons) but make no distinction of the inputs per livestock sector. E_{output} accounts for carcass, milk and eggs (excluding fats and animal offal) based on FAO Livestock Primary indigenous production. E_{input} aggregates all feed inputs of FAO Food Balance Sheets into four categories: cereals, oilcrops, annual fodder crops, grasses. Annual fodder crops include maize fodder, green fodder, pulses, vegetables, and starchy roots.

The consumption of grasses (harvested or grazed) is not reported in FAOSTAT and is difficult to quantify. However, since grasses are barely traded, we derived consumption from Agreste production statistics (Agreste, 2016) by assuming that livestock has the exclusive use of pastures. Grassland production is a key factor with high uncertainty. Inter annual variability in grassland production is backed-up by storage. However, since no data on grass stocks are available, inter-annual variability is smoothed through a linear fit. ECE is calculated in terms of gross energy using the values shown in Table 1. NCE is calculated in the same way as total proteins from the N values of table 1.

Table 1. Energy (Gross Energy) and Protein Values expressed in kcal/kg and %N of product (Fodder and Grasses in kcal/kg dry matter)

Input	Cereals	Oilcrops meal	Fodder and Grasses		
Energy	3,864	4,267	4,110		
N content	2.0%	6.0%	1.5%		
Output	Meat Beef, Sheep&Goat	Meat Pork	Meat Chicken	Eggs	Milk
Energy	3,227	3,227	3,227	1,660	707
N content	3.1%	2.1%	2.0%	1.7%	0.5%

Data sources: (NRC 2001 ; Chatzimpiros 2011; Lassaletta et al. 2014)

2.3. Disaggregation of ECE per livestock category

The reconstruction of ECE per livestock category since 1961 is a major step of the analysis. Feed inputs per livestock sector are reported from 2001 to 2010 by the French ministry of agriculture (Agreste, 2013). These records constitute the ‘witness data period’ in our analysis for the historical reconstruction of ECE per livestock category. NCE is calculated for all livestock to derive the general trajectory in parallel to the ECE calculation.

The historical reconstruction of ECE is based on the assumption that the relative change of ECE between two dates (n and $n-1$) is equal to the relative change of a productivity factor between these dates (equation 1). We define a productivity factor (PF) as the energy output per livestock head (Stock) (kcal/head/year) (equation 2). Data on livestock numbers are taken from FAOSTAT. PF is a measure of the intensification of a livestock industry (Gilbert, et al., 2015). It captures productivity changes of the entire herd as it embeds both unitary yield changes and changes in the number of production cycles. The validation condition of the assumption is that the weighted average of modeled ECE_i per livestock (i) fits global ECE from raw data.

$$\frac{PF_{i,n}}{PF_{i,n-1}} = \frac{ECE_{i,n}}{ECE_{i,n-1}} \text{ equation 1}$$

$$PF_{i,n} = E_{output\ i,n} / Stock_{i,n} \text{ equation 2}$$

$$ECE_{i,n} = E_{output\ i,n} / E_{input\ i,n} \text{ equation 3}$$

Energy inputs are calculated from equation 3 and are used to derive feed rations composition per livestock category.

2.4. Reconstruction of the ratio composition

Ration composition per livestock category is reported from 2001 to 2010 by the French ministry of agriculture (Agreste, 2013) and is used as reference for those years. For 1961, a set of feed ration percentages is computed with the constraint that the sum of energy inputs calculated per feed and animal category matches the overall energy input for livestock per feed category. The set of equations is not deterministic as there are four equations with sixteen unknowns. However, specific feeding constraints, such as that grasses and roughages are primarily consumed by ruminants, allow narrowing down the set of solutions to a handful of reasonable ration compositions. The rations for all intermediate years between 1961 and 2001-2010 are computed with a linear interpolation of the FAOSTAT feed data (see Supplementary Materials Fig S1). It's a simple approximation that fits relatively well feed availability for all livestock per feed category. . Milk used as feed is a particular case because it is an animal product embedding an ECE. We converted milk into cereals, oilcrops, fodder and grasses equivalent according to the ration composition of a milking cow with ECE of 17 % as in recent years (2001-2010).

2.5. National feed and livestock trade balances

For each feed and livestock category, we draw the national-scale product availability balance among production (Prod), imports (Imp) and exports (Exp) (FAOSTAT) to derive self-sufficiency shares per product in both energy and land (fig 2). Livestock trade includes live animals (LV reported in heads) and livestock products (LP reported in tons). LV are converted in meat equivalent using the FAOSTAT yield per animal. All imported LV are considered to be slaughtered because FAO does not distinguish LV imports in terms of final use (i.e. slaughtering vs fattening). For this reason, we slightly underestimate livestock imports.

Concerning feed balance, note the underlying assumption that the origin shares of each material are equal to the origin shares of the overall product availability in the concerned category besides that cereals have various uses (feed, food, fuel, waste and so on with potentially different origin shares per use). In parallel, we keep track of the share of a same feed and livestock in imports and exports to account for potential circular product loops in international trade.

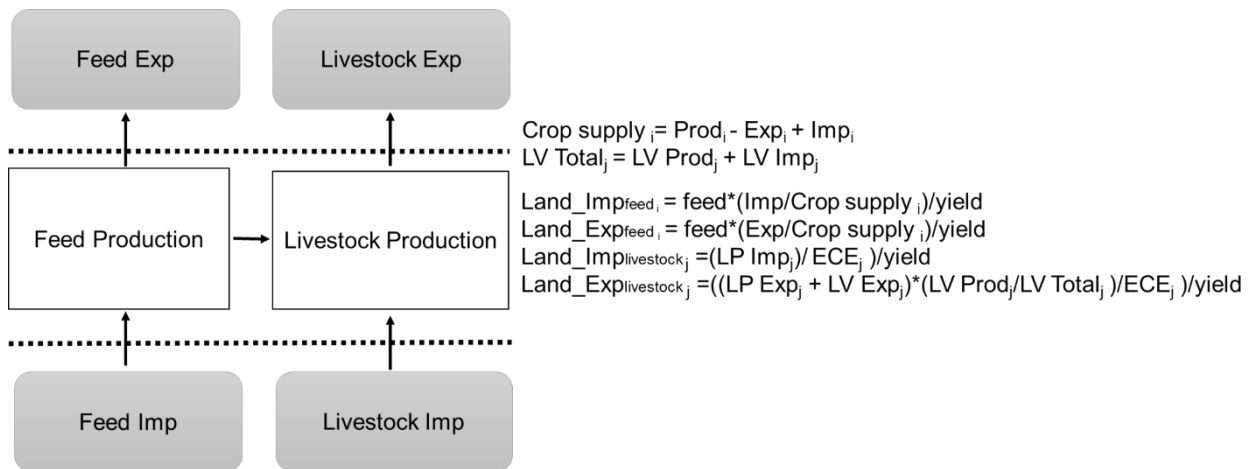


Figure 2: Calculation chart of trade balance sheets and origin shares for feed and livestock products.

2.6. Land requirements

Land requirements are obtained by dividing the amount of the consumed feed by the agricultural yield of the crop providing this feed. The direct land occupation of livestock buildings is negligible and neglected. All agricultural productivity data, including crop yields and animal rations for imported feed and livestock, are taken for France (FAOSTAT). We used wheat, rapeseed, maize fodder and grasses as witness yield data for cereals, oilcrops

fodder crops and grasses respectively. In the particular case of by-products (i.e. protein meals derived from oilcrops), the land requirement of the mother crop is allocated among the crop by-products based on energy coefficients from Chatzimpiros and Barles (2010).

3. Results

3.1. ECE efficiency

The energy conversion efficiency curves are shown in figure 1 per livestock category and for all livestock (aggregate ECE and NCE). The increase pattern of NCE for all livestock is similar to ECE and is on average 5% higher over the studied period. Model ECE and NCE data fit well with the raw data on aggregate ECE and NCE. Witness data are shown on the right part of the figure.

Overall livestock ECE is largely driven by beef and milk production and increased by 45 % from 1961 to 2010. The largest increase is for poultry with 84 %, pork increased by 17 %, and beef meat and milk by 27 %. Sheep and goat production, which only represents 1 to 2 % of total livestock production at all years, display a large ECE increase of 65 %. The efficiency of beef and milk displays a stagnation and very slight decrease during the witness period. Chicken and eggs are currently more efficient than pork following the average three-fold increase in the average number of production cycles per year.

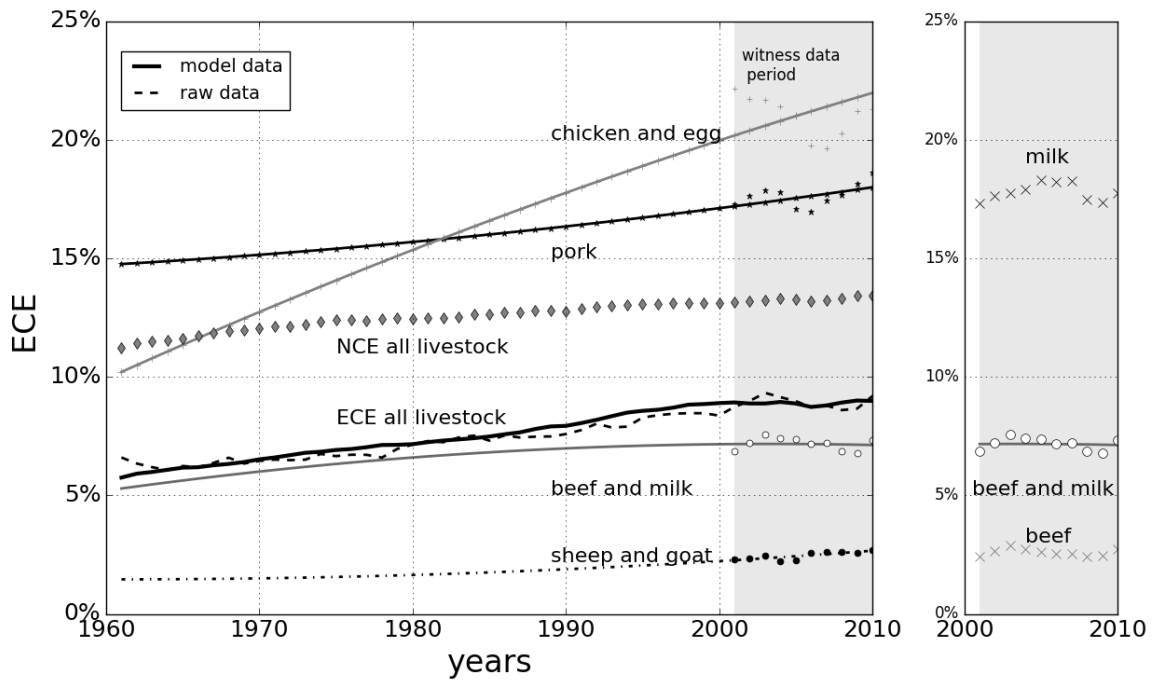


Figure 3: ECE change per livestock product. Beef and milk ECE are provided separately over the witness data period on the right part of the figure. NCE is calculated for all livestock (in thin diamond marker). Data are provided in supplementary materials *Table S1*.

Figure 4 shows the ration composition in terms of energy intake per feed and livestock in 1961 and 2010. Not surprisingly, the rations of ruminants (cattle and sheep&goat) and monogastrics (poultry and swine) display different composition. Ruminants are mainly fed grasses and annual fodder and monogastrics mainly cereals and oilcrops. However, the ration composition of each animal category also changed in time. In poultry rations, the share of oilcrops quadrupled against cereals. In swine rations, oilcrops tripled and the share of cereals further reduced a little in favor of dry grasses. Nonetheless, cereals still compose about two thirds of poultry and pork production rations. Finally, in ruminants rations, the share of annual fodder, cereals and oilseeds almost tripled against grasses.

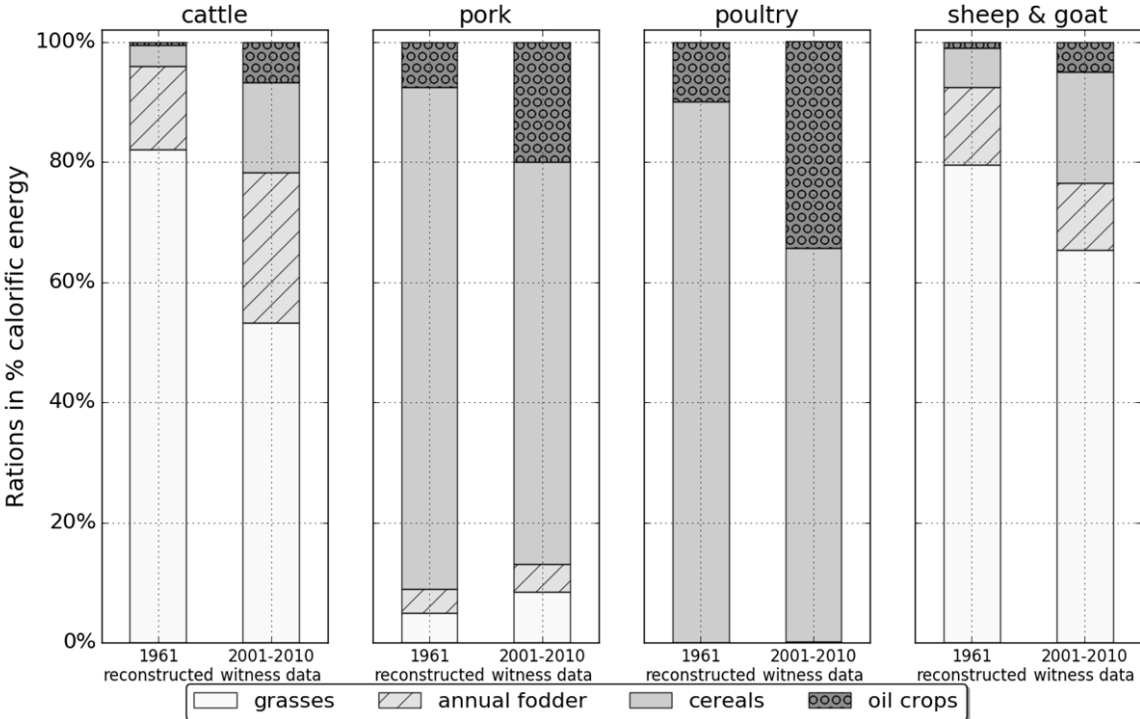


Figure 4: Feed rations composition and change per livestock. Data are provided in suppl. materials Table S2.

3.2. Land requirements

Land requirements for livestock consumption in France decreased by almost 30 % from about 19.4 million ha in 1961 to 13.5 million ha in 2010 (fig 5a). Total agricultural area in France also decreased over that period by about 17 %. Besides the decrease in land use, total livestock consumption almost doubled with a peak in the late 1990s. Per capita land use requirement for consumption dropped by 41 % to about 0.22 ha/cap today. The differential

trend between consumption and land highlights the two-fold increase in agricultural production efficiency, which is due, for half, to ECE improvement and for half to agricultural yields. The split of land requirements per feed category highlights the dominant share of roughages, which relate to beef and milk consumption. However, the share of feed from pastures decreased by 20 % over the study period (fig 5b). Cattle is the main land user, accounting for about 65 to 70% of total land requirements (fig 5c).

The share of oilcrops in land requirement increased five-fold from 2.6 % in 1961 to 14 % in the late 2000, with a slight decrease to 12.5% today. Part of the land requirements for oilcrops and by-products locates abroad. Today, oilcrops land imports for livestock consumption in France amount to 0.8 million ha against a maximum of 1.9 million ha in 1979 (fig 5c). The strong fluctuations in land requirements in 1976 and 2003 highlight the effects of droughts on crop yields, which are likely to be intensified in a context of climate change.

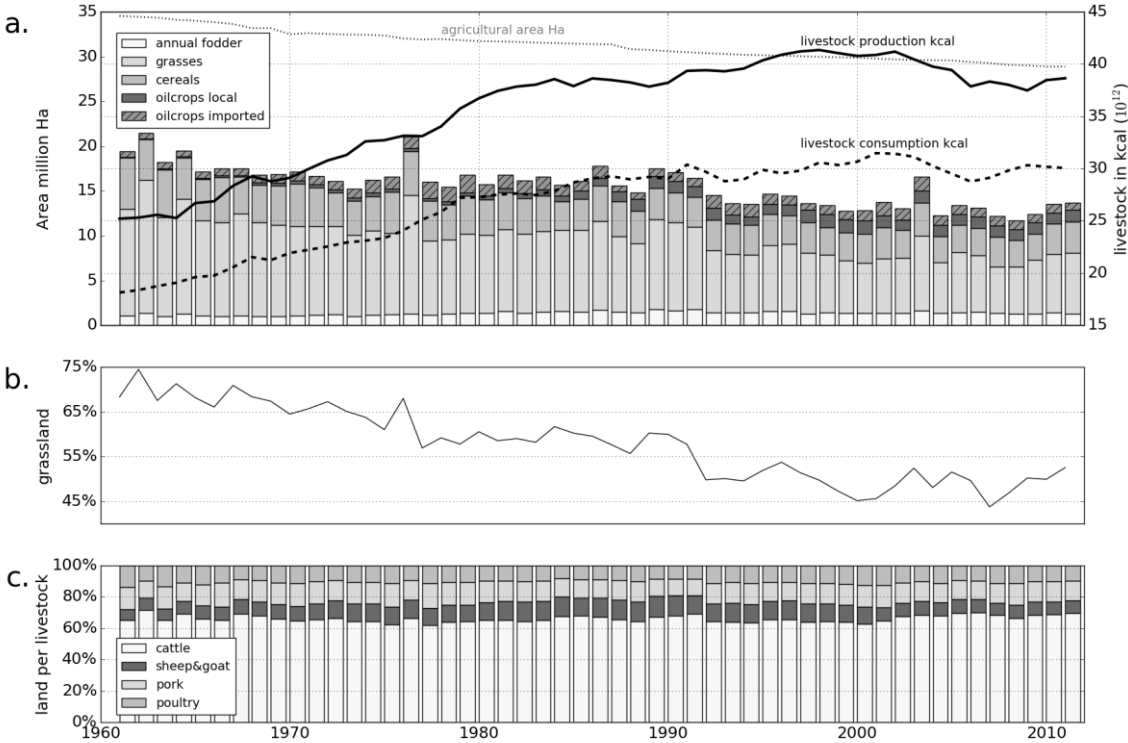


Figure 5: (a) Land requirements for livestock consumption in France per feed category. The difference between the production and consumption curves ($18 \cdot 10^{12}$ kcal today) is proportional to the difference in land requirements between production and consumption. Total land area in France is indicated on the top of the figure (b) Share of grasslands in total land use (c) Share of total land requirements per livestock category

Table 2 summarizes land requirements per unit of energy output per livestock between the 1960's and the years 2000.

Table 2. Land per unit of food energy (m2/Mcal). See suppl. materials for yearly data Table S3.

Period	beef and milk	pork	chicken and eggs	sheep & goat
1961-1970	10.1	5.5	7.8	39.7
2001-2010	5.4	2.4	2.3	16.3

France is a net exporter of cereals throughout the study period and a net importer of oilcrops. (fig 6). Cereals and oilcrops are the two main primary materials of feed concentrates. Net oilcrop imports decreased from 86 % in 1961 to 38% in 2010 because of the partial substitution of indigenous rapeseed and sunflower to imported soybean (cf. fig 6). The decomposition of total oilcrops trade per item reveals the high variability in the national supply balances and the recent trend to equilibrate the national production and consumption of rapeseed and sunflower.

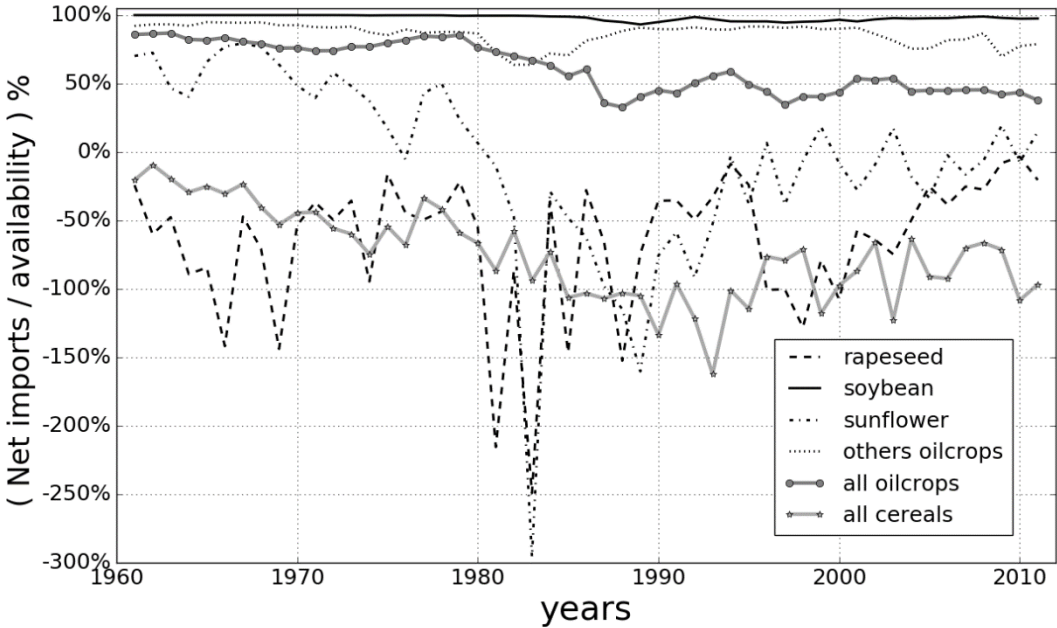


Figure 6: Net imports to availability per primary feed concentrate material

Net balances between imports and exports highlight the net land dependency of a sector but hide its actual trade activity. Figure 7a shows total virtual land trade of the French livestock sector over the study period. The French livestock sector is a net virtual land exporter (Fig 7a). Total virtual land trade was at the beginning of the period 3 times higher than the net virtual land trade while today this ratio increases to 5 times. Figure 7b indicates the share of the same feed and livestock products between imports and exports (i.e. wheat against wheat,

cattle against cattle etc.) suggesting that a same product is more and more exchanged at the international scale, probably at different production stages among countries. The increase in the share of common products between imports and exports is much greater for livestock than for feed.

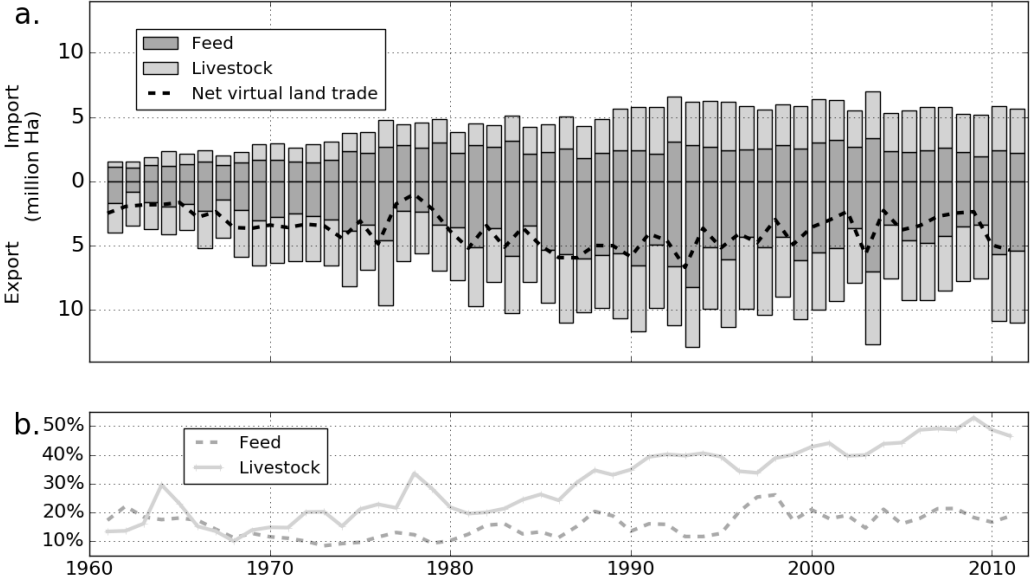


Figure 7: (a) Total virtual land trade of the French livestock sector (10^6 ha) (b) Share of the same feed and livestock between imports and exports

4. Discussion

This paper calculates energy conversion efficiency (ECE) of livestock production in France in historical perspective and connects consumption of products to land requirements, while keeping track of both net and total virtual land trade in livestock systems. Consumption based approaches on resource use in historical perspective provide insights for policy makers as they reconstruct macroscopic phenomena and their gradual evolution in time from seemingly disconnected sectorial data.

Our model reproduces well the available raw data on total feed availability and aggregate ECE throughout the study period. Deviations are higher at the beginning of the period and may be due to the use of feed such as straw that do not appear in the statistics. Straw is often used as a back-up feed to compensate for local feed deficits due to inter-annual agricultural productivity variations. Macroscopic estimates of its actual use can only be reflected by modeling approaches such the one presented in this paper. Today, under normal productivity

conditions only about 1 % of total straw production is used as feed (Agreste, 2013) but this share is likely to fluctuate with climate or other instability factors affecting agricultural productivity. Concerning the deviations between the reconstructed and the actual feed use per feed category (supplementary materials, figure S1), they indicate that the linear approximation of rations composition overestimates the use of cereals and underestimates the use of grasses between the 1980's and the years 2000. The discrepancy most probably derives from cattle rations composition and does not affect our results of ECE nor the general trend of significant substitution of grasses by cereals in cattle rations over the study period.

ECE is among the ways to connect livestock products to their feed equivalent and to account for associated land and resources. Other accountings that allow comparing products on a nutritional value base include mass or proteins conversion efficiencies. Both mass and NCE typically yield higher conversion efficiency figures than ECE. Aggregate NCE is here found 5 % higher than ECE throughout the study period. However, production efficiency varies with production system management (Chatzimpiros, 2011). Shepon et al. (2016) report higher energy than protein conversion efficiency for dairy and beef production, the inverse for poultry and eggs production and equal for pork production. A systematic comparative analysis between ECE and NCE in time could provide interesting insights on differential energy to protein optimization in agriculture. Such an analysis is out of the scope of this paper. Our results for France correspond to ECE levels for industrialized livestock systems.

Discrepancies in livestock efficiency in relation to agricultural industrialization highlight that ECE is not a time invariant. Time series of ECE are barely reported in the scientific literature. All previously cited studies focus on single time point because of lack of appropriate data on feed inputs (Shepon et al., 2016 ; Wirsenius et al., 2010 ; Smil, 2002, Chatzimpiros and Barles, 2010). Our approach assesses ECE change per livestock category over the last 50 years based on livestock herd composition and production data, which makes it a major contribution in agricultural resource use assessments.

Throughout the study period, the ranking of ECE changed between pork and poultry, while cattle remain by far the lowest ECE production. One should bear in mind that the calculated ECE for cattle is specific to the share of milk and meat in total production and hides the 6-fold efficiency difference between milk and beef (Smil, 2002, Chatzimpiros, 2011). However, aggregate cattle ECE provides a good estimate of the efficiency of total cattle herds.

Beef production has the lowest ECE and is therefore the most land demanding production per unit of kcal output. Today, together beef and milk supply 55 % of total livestock consumption

in France against 62 % in the 1960's and account for about 65 to 70 % of land requirements over the study period. Indeed, the relative efficiency of cattle decreased in France over the study period due to the comparatively greater productivity increase of the poultry and pork sectors. These latter mainly use feed crops, which agricultural yields increased faster than for grasslands. Beef meat consumption is, therefore, by far more land consuming than poultry and pork consumption (cf. Table 2). However, cattle are much less demanding on high quality cropland than the poultry and pork sectors. Indeed, cattle consume pastures and therefore convert low quality feed to high quality food with less direct competition with human food crops. From this point of view, cattle are the most autonomous livestock in terms of feed supply and contribute in preserving semi-natural ecosystems, characterized by relatively lower environmental externalities on water quality and biodiversity than crop monocultures (Chatellier & Vérité, 2003; Steinfeld & Gerber, 2010).

The increase in the production efficiency of livestock came along with changes in diets and rations composition. In particular, the share of poultry in total meat consumption in France doubled, while beef decreased about 30 %. Overall, the share of oilcrops in animal rations in France has increased ten-fold since 1961 and their share in land requirements has more than quadrupled. Oilcrops are used as protein supplements mainly in swine and poultry rations and are largely imported from abroad. Therefore, besides a total reduction in land use, the dependence of the French livestock sector on imported feed has increased along with changes in the animal rations composition. Rations composition change has even affected cattle. As shown in fig 5b, the dependence of cattle on land other than grassland has increased from about 25 % in the 1960's to 50 % in the early 21st century. Accordingly, cattle are now a much greater competitor of highly productive cropland, which could otherwise be more efficiently allocated to directly feed humans. The share drop of pastures in total feed production (cf. fig 5b) is a measure of this growing competition. Wilkinson (2011) has already highlighted that the increase in grain use for livestock is a counterweight to their increasing efficiency.

In addition, changes in livestock efficiency in time reflect changing resource use patterns in production systems. For instance, the spectacular increase in the ECE of poultry production is due, in part, to the mastery of the production conditions. In industrial poultry systems, the birds are dispatched in buildings by age and the production efficiency of each stage relates to the inside air temperature translating to additional energy use (ITAVI, 2008). A full

accounting of resource inputs as both feed and other fuels lacks in the scientific literature and is essential for assessing overall energy efficiency change in production systems.

Since the 1980's, the share of net oilcrop imports in France has decreased from more than 80 % to less than 40 % as a result of rapeseed to soybean cake substitution in rations. A main driver for this change is a consistent European policy of the last decades, in support of rapeseed and sunflower crop development for biofuels and feed self-sufficiency (AFD, 2011). Following a period of high fluctuations in the oilcrops trade balance of France, the country currently adjusts its national production of rapeseed and sunflower to its domestic use of cakes from these crops (cf. fig 6).

Nonetheless, soybean cake imports are still very significant. The French livestock sector is dependent on external feed besides its overwhelmingly positive feed trade balance between oilseed and cereals (cf. fig 7a). Indeed, since different feed categories have different nutritional properties, they cannot be considered as substitutable in land trade accountings. Feed deficits and surpluses have to be accounted for per crop category to accurately assess the degree of self-sufficiency of a sector. In addition, total trade activity is usually different from the net trade balance of a sector because net feed deficits and surpluses are not the only reason for trade (fig7a, b). Our results highlight that part of the difference relates to the fact that countries often import and export a same product. For instance, France imports small quantities of cereals as feed besides being a notorious net exporter of cereals. Similarly, the French livestock sector massively exports live animals of a given category and imports foreign meat of the same category. The sum of livestock products that are common between imports and exports is today about 50 % against 12 % in 1961 (fig7b). In sum, today virtual land imports and exports correspond respectively to 2.4 and 5.7 million ha for feed and to 3.5 and 5.1 million ha for livestock. In the case of livestock, the increasing share of same products in imports and exports possibly indicates an increasing integration and subsequent specialization, at the international scale, of gestation, calving, fattening and slaughtering stages of livestock systems. A complete analysis of international livestock trade networks per country of origin and destination of products could effectively reveal in detail the complex circular flow loops among countries. Today worldwide, about 20 % of food product exports of countries are on average previously imported (Agreste, 2017). Total virtual land trade better reflects market interdependencies than net virtual land trade.

Part of the total land trade reflects the European oilcrops sector integration among countries between production and processing stages. For instance, France exports most of its rapeseed and sunflower production to Germany, Belgium and the UK from where it reimports protein meals after the extraction of the oil of seeds. Production chains and markets are thus increasingly integrated among countries through economies of scales. The increasing transport distances involved in international integration has gone hand in hand with a regional clustering of the production activity. Feed and livestock production are today highly spatially concentrated and geographically decoupled in distinct regions. Geographical decoupling of livestock from cropland induces a local disintegration of nutrient loops, hampering nutrient recycling and increasing environmental food-prints (Chatzimpiros and Barles, 2013, Leip et al 2015). The specialization of French Brittany in pork production is an emblematic example of vertical integration of a production sector with high dependence on imported feed. Brittany concentrates today about 60 % of total French pork production against 13% in 1961 (Agreste 2016, SAA 1961) and Breton farms are for about 80 % dependent on feed (cereal and oilcrop) imports (Chatzimpiros, 2011).

Beyond the numerical results for France, this paper provides a comprehensive powerful methodology for calculating production efficiencies and land use trade from easily available data on livestock numbers and productivity factors. The methodology is applicable to all scales. FAOSTAT data may support international comparisons among countries or larger world regions with contrasting structures of livestock systems. It may provide insights on regional feed deficits in relation to production practices and/or consumption patterns and support a monitoring of changing land use allocation to and among livestock sectors. Additionally, the production efficiency per livestock can be a basis for eco-labeling to inform consumers on meat consumption choices. Relevant labeling information could include animal rations composition, feed origins and farms feed self-sufficiency, total nutrient losses, conversion efficiencies or land requirements for consumption. Such information could contribute in raising awareness by transferring sound environmental knowledge to the civil society about the resource use equivalent of diets. Moreover, the historical data reconstruction methodology presented in the paper can support prospective assessments of land requirements for livestock activity in relation to productivity factors projections.

5. Conclusion

The paper provides an historical assessment of changing land use allocation in France in relation to livestock production and consumption and associated virtual land trade. ECE calcula-

tion per livestock category is a major contribution of this work. It allows relating livestock production and consumption to resource use and environmental impacts for any resource. It highlights differential trends in livestock productivity increases among different livestock over time. It provides insights on characteristic times of productivity change per livestock sector and may support prospective assessments of productivity increases and associated resource use rates. Total land use of the French livestock sector reduced by 28% in fifty years besides a 53 % increase in total product output. Changes in rations composition have been in favor of higher use of feed from arable land even for cattle. Traditional feed from grasslands reduced by 25% in cattle rations in favor of cereals and oilseed cakes. In sum, the French livestock sector is a net exporter of virtual land but remains a net importer of land relating to protein feed concentrates. Protein concentrate feed deficits are significant but are progressively shrinking. Because of increasing international agricultural market integration, total virtual land trade is growing over time and is remarkably higher than net virtual land trade. Therefore, total virtual land trade better reflects the extent of market interconnections and integration than net virtual land trade. The work is likely to provide useful insights for policy making on feed and livestock products self-sufficiency and associated resource use monitoring issues. It may also contribute in raising awareness on the resource use of consumption choices per livestock product as well as support projections of land requirements in relation to productivity factors projections.

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