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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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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 production 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 the human population and by 53% of the 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 2.5–5.3 million ha per year over the study period. Gross 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.

1. Introduction

Livestock production holds a central and growing share in agricultural production systems. Huge quantities of agricultural products go into animal feed production. The total land area involved in livestock production is estimated to about 70% of all agricultural land, which is about 30% of all ice-free terrestrial surface of the planet (Steinfeld, 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 and 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 and Bruinsma, 2012). The projected increase outpaces demographic growth and will necessarily entail additional feed requirements and environmental pressure in relation to the production of this feed.

The livestock conversion efficiency of feed to 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., 2011), consumption and pollution of water resources (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 per production unit 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

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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 and international trade.

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 production often from single crop systems 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 and on associated virtual land trade in historical perspective based on a calculation method using easily available 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 livestock productivity. 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 gross trade, which is the absolute sum of all agricultural trade of a sector. This provides a more complete picture of the international 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 & goat. The four categories together account for more than 97% of livestock production and consumption in France. Fig. 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 includes the following five main steps: (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.

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 use 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 (defined as indigenous animals slaughtered, plus the exported live animals of indigenous origin, see FAO definition, FAO, 2011). E_{input} groups feed materials into four categories: cereals, oilcrops, annual fodder crops and grasses. Cereals and oilcrops are derived from the FAO Food Balance Sheets (FAOSTAT, 2016). Annual fodder crops include maize and green fodder, pulses, vegetables and starchy roots and are derived from FAOSTAT (2016) except from maize and green fodder which are no longer reported in FAOSTAT and are derived from Agreste (2016a). Grasses is a particular case. 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, 2016a) by assuming that livestock has the exclusive use of pastures. Grassland production is a key factor with high uncertainty and is estimated by Agreste through an integrated agro-pedo-climatic modeling tool (i.e. Agreste, 2016b).

Annual variability in grassland production is backed-up by inter-annual grass 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 using the nitrogen (N) values of Table 1.

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 only 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 (Eq. (1)). We define the productivity factor (PF) as the energy output per livestock head (Stock) (kcal/head/year) (Eq. (2)). Data on livestock numbers are taken from FAOSTAT. PF captures productivity changes of the entire herd as it embeds both unitary yield changes and changes in the number of production cycles. It is thereby an indicator of the intensification change of a livestock industry (Gilbert et al., 2015). The validation condition of the assumption is that the weighted average of modeled ECE_i per livestock *(i)* fits global ECE from raw data.

$$\frac{PF_{i,n}}{PF_{i,n-1}} = \frac{ECE_{i,n}}{ECE_{i,n-1}} \quad (1)$$

$$PF_{i,n} = E_{output\ i,n}/Stock_{i,n} \quad (2)$$

$$ECE_{i,n} = E_{output\ i,n}/E_{input\ i,n} \quad (3)$$

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

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	3864	4267	4110
N content	2.0%	6.0%	1.5%

Output	Meat Beef, Sheep & Goat	Meat Pork	Meat Chicken	Eggs	Milk
Energy	3227	3227	3227	1660	707
N content	3.1%	2.1%	2.0%	1.7%	0.5%

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