HOW TO FEED THE WORLD: IS REDUCING MEAT CONSUMPTION PART OF THE SOLUTION?

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Abstract - Consumption of animal products, notably meat, and livestock production should continue to rise worldwide in a business-as-usual scenario under the influence of both demand and supply factors (demography, economic growth, urbanization, improvements in livestock breeding and feeding, *etc.*). This does not mean that feeding the world in 2050 and beyond is not possible, but achieving this objective requires strong economic growth worldwide and would be obtained at the price of a worsening of local and global environmental problems linked to food and agriculture. A departure route can be followed in which consumption of animal products is significantly lower in 2050 compared to a business-as-usual scenario, and pressures on the environment from food and agriculture substantially reduced. Does this comparison of two contrasted foresight scenarios mean that reducing consumption of animal products is the solution, or at least part of the solution, for feeding the world in 2050 and beyond? Things are not so simple. If reducing excessive consumption of animal products, notably meat, can be recommended for health reasons, such a reduction is not advisable for poor households who lack protein in diets. If livestock production, notably grain-fed livestock, presents several land, energy and environment drawbacks, it also presents benefits, notably in developing countries and/or in grass-based systems. In addition, considering the food security issue at the global level is not sufficient. Considering efficiency differences linked to animal species and races, feeding rations and livestock systems are essential.

I. Introduction

From the beginning of the 21th century, the issue of global food security has received increased scrutiny. A large number of perspective or foresight studies concerned with the ability of the world agricultural and food system to feed the projected world population in 2030 and/or 2050 have been published. Among them, the FAO report entitled “World Agriculture towards 2030-2050” (Alexandratos and Bruinsma, 2012) is very likely the most well-known projection exercise. It is very often held as a reference for baseline projections of world agricultural supply and demand. The most striking result of the Alexandratos and Bruinsma study is that world agricultural production has to increase by 60% to satisfy global demand in 2050 (compared to production level in 2005/2007). This 60% increase in production would come mainly from an increase in crop yields (80% of production rise at the world level), some increase in cropping intensity (10%) and limited agricultural land expansion (10%).

Even if this FAO figure or similar figures proposed earlier by this international institution (Bruinsma, 2003; FAO, 2006; Bruinsma, 2009) have been very publicized and used by several interest groups as an argument for greater intensification of agricultural practices and systems, in favor of intensive use of genetically modified organisms (GMOs) or against development at large scale of organic farming, the underlying methodology and assumptions are poorly documented which means that using this 60% production increase without any accompanying information and precaution is not very meaningful (Grethe *et al.*, 2011). However, as noted by Grethe *et al.* (2011), the FAO figures have clearly induced an excessive focus on food supply and the need of an increase in global agricultural production. Alongside agricultural production and productivity increase, there are however several other production and consumption levers that could be used for feeding the world in a sustainable way. These levers include reducing food losses and waste along the whole food chain, limiting public policies aiming at developing first-generation biofuels from crops that can also be used for food or feed, and decreasing consumption of animal products, notably meat, because animals are less efficient than crops in transforming solar energy into calories. Reducing non-food uses of agricultural biomass and consumption of animal products relies mainly on the argument that there will be not sufficient land at the world level for feeding the world's growing billions. This paper specifically addresses the issue of livestock production and consumption of animal products, notably meat. This specific issue is more particularly analyzed in terms of land availability and land area required for feeding livestock. On the other hand, it is broadened in the more general context of all parameters of the global food security equation. The remaining of the paper is organized in five sections.

In Section 2, we illustrate that changes in livestock production and consumption of animal products have been very significant worldwide over the last decades under the influence of a large number of supply and most importantly demand side determinants.

In Section 3, we show that livestock production and consumption of animal products, notably meat, should continue to increase over the next decades in a business-as-usual scenario because the same drivers that have been in place in the past decades should continue to exert a positive pressure in the future (Sans and Combris, 2015; Mathijs, 2015). However, this does not mean that it would be not possible to quantitatively feed the world in 2050 in a business-as-usual scenario. This will be illustrated by the first scenario of the Agrimonde foresight study (Paillard *et al.*, 2010). This outcome however requires strong economic growth worldwide and furthermore would be achieved at the price of a worsening of local and global environmental problems. This means in particular that even if there is cultivable arable land that is not cultivated yet, a continuation of current trends in the production and uses of the various sources of food biomass in a more and more liberalized world would not be environmentally sustainable because of unsupportable pressure on the environment (fossil energy, soil, water, air, greenhouse gas emissions and biodiversity). This unsupportable pressure results from both land conversion towards agricultural use (impact at the extensive margin of production) and an increasing use of water and chemical inputs on cultivated land area (impact at the intensive margin of production). Furthermore land surfaces not yet cultivated are very unevenly distributed worldwide which implies that international and regional agricultural trade, including trade in feed products, animals and animal products, should substantially increase in a business-as-usual scenario: how to secure this trade is a key issue.

In Section 4, we show that a very different way can be followed in which all demand and supply side drivers of the world food security equation are simultaneously mobilized: reduction of harvest, pre-harvest and post-harvest losses, diminution of non-food uses of agricultural biomass, changes in consumption patterns including in particular less meat consumption in developed countries and from the most richer households of emerging and even developing countries. This alternate way will be illustrated by the second scenario of the Agrimonde foresight study (Paillard *et al.*, 2010) in which food availability reaches 3 000 kilocalories/capita/day in 2050 in all regions of the world, of which 500 are of animal origin. This means a meat consumption decrease in some parts of the world, notably in OECD (Organization of Economic Co-operation and Development) countries, stagnation in Latin America and the former Soviet Union, and an increase in Asia and sub-Saharan Africa.

Because livestock production is less efficient than crop production in transforming solar energy into food calories, it is clear that limiting increases in consumption of animal products from current levels would help solving the world quantitative food equation. Such a limitation could also have positive effects on both health and environment indicators. Nevertheless livestock production and consumption of animal products deliver benefits that have to be taken into account. In that context, improving the land, energy and environmental footprint of livestock production and trade, including induced production and trade of crops for feed, is a priority for research, extension and stakeholders. In that perspective, Section 4 analyzes more specifically the question of land areas mobilized for feeding the world livestock. This question will be explored on the past (retrospective analysis) and for the next decades, at both the world and regional level.

The final section concludes.

II. Impacts of the westernization of world eating patterns on the livestock industry

2.1. Evolution of eating patterns

Eating patterns worldwide present some common evolutions and characteristics that can be summarized as follows: (1) world diets are converging and the process that began in developed countries is now extending to an increasing number of emerging and developing countries at an accelerated rate[1]; (2) the food chain is becoming increasingly complex as food products are more and more processed, sophisticated and ready-to-eat; (3) food products are increasingly sold in supermarkets and eaten away from home; (4) food losses and waste are substantial; and (5) the gap is widening between agricultural production and producers on the one hand and food consumption and consumers on the other hand (Guyomard *et al.*, 2012). One essential characteristic of this westernization of world food diets is the increasing consumption of animal products, notably meat, that translates into changes in livestock production on the supply side.

The nutrition transition process characterizing the convergence of world eating patterns includes a first step, mainly quantitative, corresponding to an increase in the calorie intake with roughly proportionally equal rises in all food products. Once calorie saturation is achieved, diet structure changes in a second step. Consumption of cereals, staple foods and pulses decreases while consumption of sugars, fats and oils, fruits and vegetables as well as products of animal origin increases (see Figure 1.1 for an illustration in the case of France). As a result of this two-step nutrition transition process, world per-capita consumption of animal products has experienced a huge increase over the past decades, especially since the 1980s (see Figures 1.2 and 1.3). According to Grethe *et al.* (2011), per-capita consumption between 1980 and 2005 increased by 64 % for eggs (from 5.5 to 9.0 kg/year), by 37 % for meat (from 30.0 to 41.2 kg/year) and by 9 % for milk (from 75.7 to 82.1 kg/year). According to Combris (2015), meat consumption rose worldwide from 23.1 kg/person/year in 1961 to 42.2 kg/person/year in 2011 or, equivalently, from 9 g/person/day in 1961 to 15 g/person/day in 2011. As the same was true for all proteins from animal origin, total consumption of animal-based proteins increased from 23 g/person/day in 1961 to 36 g/person/day in 2011 (+ 50%), to compare with the much slower increase in consumption of plant-based proteins (+ 16%,

[1] According to Popkin (2006), the transition is reduced to around 20 years in developing countries and to around 40 years in other developing countries.

from 38 g/person/day in 1961 to 44 g/person/day in 2011).

Figure 1.1. Secular trends in France in the daily calorie intake (left panel a) and in the structure of the diet (right panel b). Source: Guyomard *et al.* (2012) from Combris (2006)

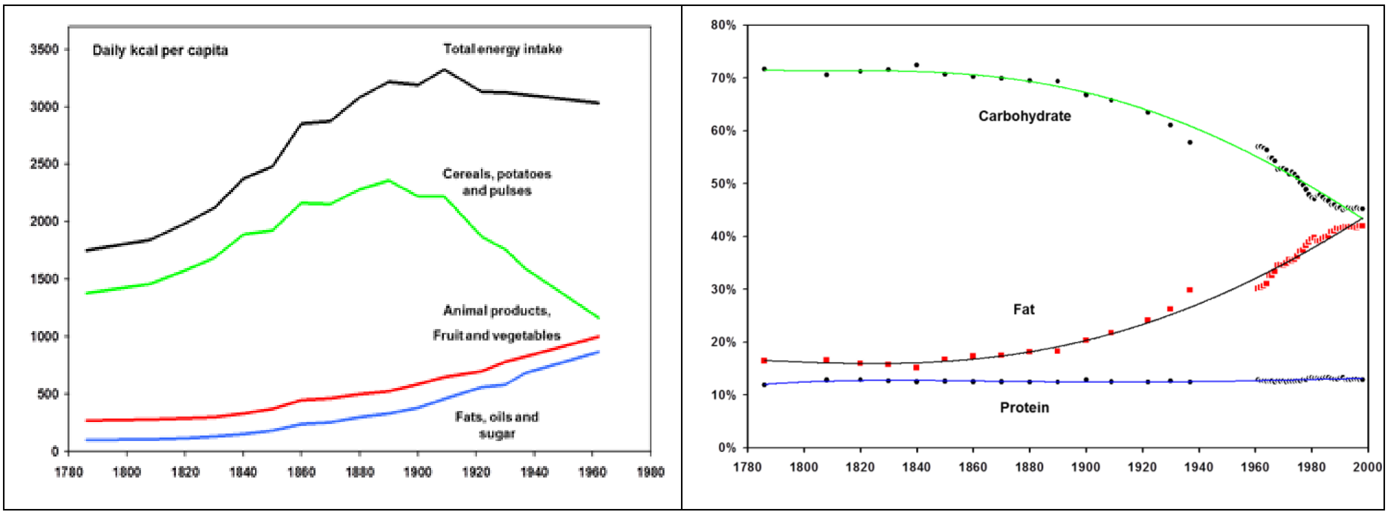


Figure 1.2. Evolution of total calories and calories from animal products (kilocalories/person/day) in various developed, emerging and developing countries, 1961-63 to 2003-05. Source: Guyomard *et al.* (2012) from Combris (2009)

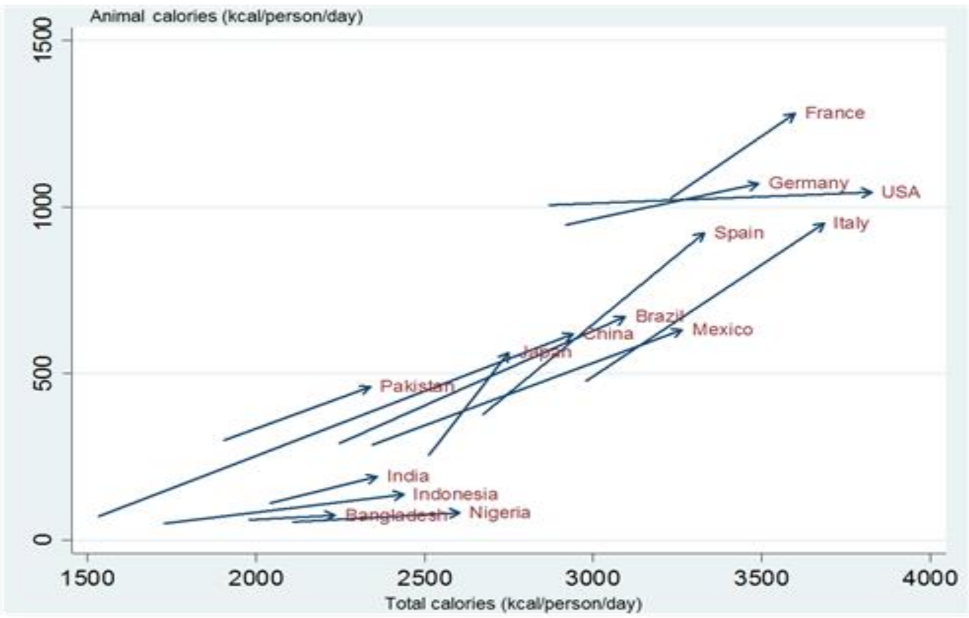
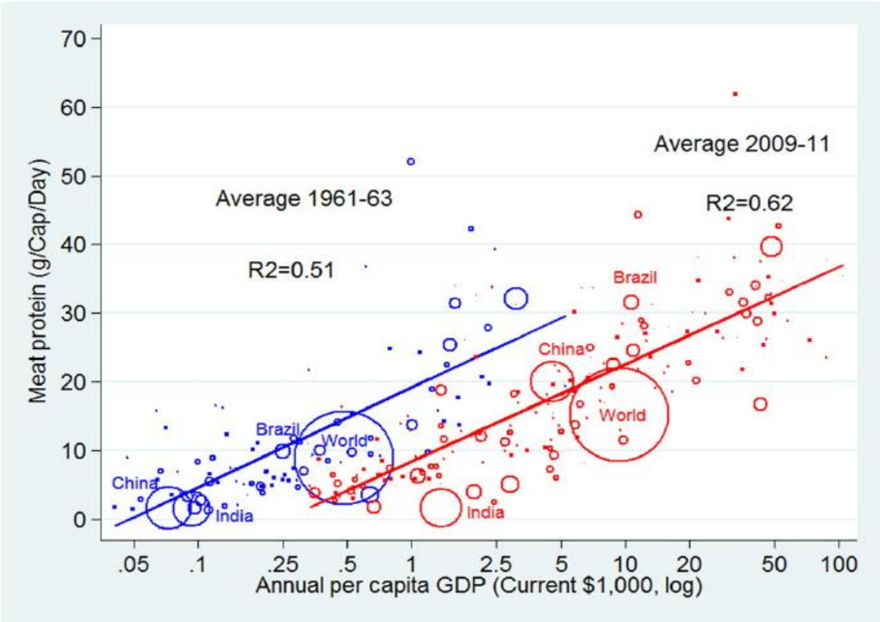


Figure 1.3. Changes in protein from meat versus per-capita Gross Domestic Product (GDP). Source: Combris (2015)



The animal-based protein consumption increase was much more important in developing states than in developed countries where consumption levels in the 1980s were already at a high level : in the case of meat, 76.3 kg/person/year in developed countries to compare with only 14.1 kg/person/year in developing countries. The impressive growth in consumption of animal products is furthermore unevenly distributed, concentrated in a limited number of countries, notably in East and Southeast Asia, where economic growth was the most important (Pica-Ciamarra and Otte, 2009). As a result, diet differences remain between countries even when they are at an identical level of economic development. This can be illustrated by consumption of beef, pork and poultry meat in European countries: according to Combris (2006), consumption levels in 2003 ranged from 13 kg/person/year in Germany to more than 26 kg in France in the case of beef; from 28 kg/person/year in the United Kingdom to 56 kg in Germany and 62 kg in Spain in the case of pork; and from 15-16 kg/person/year in Germany and Italy to 28-29 kg in Spain and the United Kingdom in the case of poultry. This means that even if economic growth and urbanization drive the convergence of food diets worldwide, other factors have to be taken into account in order to understand differences in eating patterns that can still be observed for an identical level of economic development. Among these factors are cultural, ethical and religious differences. For example, De Boer *et al.* (2006) suggest that meat consumption is significantly higher in predominantly Catholic European countries than in predominantly Protestant European Countries in part because of the relationship of the Catholics with meat eating (social marker and eating pleasure).

To conclude, it is worthwhile noting that some authors (Vranken *et al.*, 2014; Mathijs, 2015) suggest that that the first two steps of the nutrition transition process are (or will be) followed by a third step corresponding to more fruit and vegetables and less fat and meat because of increasing awareness of the health implications of dietary choices.

2.2. Evolution of livestock production and trade

Changes in livestock production have been similarly impressive over the past decades. World meat production has increased from around 120 million tons in 1970 to more than 270 million tons in 2010. Between the two same dates, world milk production has increased from around 400 million tons to more than 690 million tons. As in the case of the consumption, the annual growth rate of meat and milk supply has been much higher in developing countries than in developed countries (in the case of meat, respectively + 8.1% and + 1.9%).

The key drivers of changes in the whole livestock industry are demand driven, led primarily by economic growth, demography and urbanization. But the so-called livestock revolution (Delgado *et al.*, 1999) has also roots on the supply side, notably improvements in genetics, breeding and feeding (Thornton, 2010). A direct consequence of this revolution is a switch in the domestic use of agricultural biomass from human consumption to feeding of livestock. Even if ruminant production can mobilize marginal lands that have no other use options, livestock production relies more and more on resources that can also be used for food under the combined effect of a first shift from ruminants to monogastrics (Bouwman *et al.*, 2005) and a second shift from grass and low-value feed ingredients (residues) to feed concentrates induced by the industrialization and intensification of livestock production, notably in the case of pork and poultry.

Despite huge increases in livestock production in developing countries, the latter continue to depend on imports from developed and emerging countries for satisfying their needs in animals and animal products. As a result, world trade in animal and animal products is growing faster than livestock domestic production with a trebling over the last two decades. This means that trade in animals and animal products is essential for satisfying consumption needs, and ultimately achieving global food security. Trade is essential all the more as it does not restrict to animals and animal products but also includes cereals and oilseeds (in the form of cakes) for feeding domestic livestock.

III. Will it be possible to quantitatively feed the world's growing billions if consumption of animal products continues to rise?

The first scenario of the Agrimonde foresight study shows, or more precisely suggests, that it would be possible to quantitatively feed 9 billion people in 2050 even in the case where world consumption of animal products continues to rise. This is however achieved at the expense of the environment and the agricultural use of fossil resources.

This first scenario called Agrimonde GO is based on the principles of the Global Orchestration scenario of the Millennium Ecosystem Assessment (MEA 2005). It depicts the consequences of a continuation of trends in production and consumption patterns. In a more and more liberalized world, priority is given to economic growth and the material well-being of current generations. Huge investments in education, health, infrastructures, research and innovation are possible thanks to economic growth and technical progress spreads throughout the whole planet.

Food consumption in 2050 is driven by demography, economic growth and urbanization. It increases in each region to reach a minimum of 3 000 kilocalories/capita/day in sub-Saharan Africa (2 320 in 2000) and a maximum of 4 100 kilocalories/capita/day in OECD countries (3 940 in 2000)[2]. Consumption of animal products rises in all regions, from 133 to 283 kilocalories/capita/day in sub-Saharan Africa and from 1 167 to 1 628 kilocalories/capita/day in OECD countries. Poverty is

[2] The Agrimonde foresight study distinguishes six regions, that is Asia (ASIA), the Former Soviet Union (FSU), Latin America (LAM), Middle-East and North-Africa countries (MENA), the OECD zone (OECD) and sub-Saharan Africa (SSA).

significantly reduced along with the number of undernourished people. At the same time, diseases due to over-nourishment continue to increase: diabetes of type II, coronary heart disease, cancers, osteoarthritis, work disability, sleep apnea, *etc.* (Visscher and Seidell 2001).

To satisfy this increased food demand as well as the rise in non-food uses of biomass, agricultural production increases in all regions under the influence of two main factors, an expansion in the area of agricultural land and most importantly an increase in agricultural yields.

At the world level, cultivated land used for food, feed, fiber, chemistry and energy increases by + 23% over the period 2000-2050 and pastureland increases by + 7%. These global figures mask huge disparities among regions. While cultivated land area increases in all regions at however significantly different rates (around + 10% in Asia, the Former Soviet Union, MENA countries and the OECD zone, but around + 60% in Latin America and sub-Saharan Africa where cultivable land not yet cultivated is most important), pastureland decreases in some regions (FSU and OECD), is stable (LAM and MENA) or increases (ASIA and SSA). While the world deforestation rate is significantly lower compared to the 1961-2000 period (respectively, - 1% and - 9%), forests disappear at a much higher rate in the two African zones (- 31% in SSA and - 35% in MENA). This evolution of land under culture, pasture and forest drives clear negative environmental impacts at the extensive margin of production in regions where cultivated land area increases at the expense of pastureland and forest (LAM, MENA and SSA): biodiversity loss, reduction in carbon storage, *etc.* A second negative environmental effect at the extensive margin of production occurs because of the expansion of cultivated land in all regions, this cultivated land being not managed in a sufficiently sustainable way.

In effect, in the Agrimonde GO scenario agricultural production systems are increasingly similar worldwide. They correspond to an “industrial’’ model of agriculture based on an intensive use of mineral fertilizers, synthetic pesticides, green biotechnologies, *etc.* to the detriment of local know-how and diversity, notably in terms of vegetal and animal species, varieties and/or races. In other words, the Agrimonde GO scenario relies on increasing yields but does not assume that the sustainability of agricultural systems improves significantly. All conditions are set for an explosion of local and global environmental problems. But plans are not necessarily made to address them. Environmental concerns come second to the more pressing issue of immediate food and non-food uses. Environmental problems are only tackled reactively, and there is no real push to cut greenhouse gas emissions, including emissions from the agricultural sector, despite available financial resources and a favorable economic context. In a general way and while this outcome is not explicitly stated and demonstrated, the Agrimonde GO scenario assumes that it would not be possible to significantly improve the environmental footprint of agricultural systems if they continue to intensively rely on fossil energy and synthetic chemistry.

IV. Feeding the world in 2050 in a sustainable way: is reducing meat consumption part of the solution?

The livestock sector is increasingly questioned on the basis of both supply and demand reasons. Supply side critics rely on the fact that significantly more resources are required to produce a kilogram of animal products than a kilogram of plant crops. According to Basch *et al.* (2012), beef requires up to 8 kg of feed for every kg of meat produced at the world level. Corresponding figures are equal to 5 for lamb, 2.5 for pork, 1.5 for poultry and 1.2 for fish. According to Smil (2000), of the 1 700 kilocalories/person/day used for animal feed at the world level in the end 1990s, animals return only 500 thus having an animal-product-to-feed conversion rate of 0.29. In the specific case of the United States, Leibtag (2008) considers that 7 kg of feed are needed to produce 1 kg of beef and 2.6 kg of feed are required to produce 1 kg of chicken. Even if these figures can rightfully be questioned (see

Section 5), the fact that animal production is less efficient than plant crops in transforming solar energy into calories is certain and raises the question of land competition between crops grown for direct human consumption and crops grown as inputs for raising livestock, and to a lesser extent fish in aquaculture. According to Steinfeld *et al.* (2006), around 33 % of the world cropland would be devoted to feed crop production. This competition between food and feed would be increasing because of the growing industrialization of the livestock sector and the scarcer availability of natural grazing area and plant residues. According to Grethe *et al.* (2011), livestock production would be the primary driver of deforestation. In addition, significantly more water is required to produce a kg of animal products than a kg of plant crops and livestock production is responsible for 18 % of world greenhouse gas emissions[3]. On the demand side, the consumption of animal products is questioned essentially because food diets less rich in meat would be better for health. We will also discuss the validity of this argument.

These arguments against production and consumption of animal products, whatever their reality, have led many researchers to consider food perspective scenarios in which meat demand in developed countries is reduced compared to a business-as-usual reference scenario (Rosegrant *et al.*, 1999; Stehfest *et al.*, 2009, Wirsenius *et al.*, 2010; Grethe *et al.*, 2011)[4].

This is also the route followed in the second scenario of the Agrimonde foresight study (Paillard *et al.*, 2010). In this second scenario called Agrimonde 1, under the joint effect of climate change and the succession of energy and food crisis during the beginning of the foresight period (2010-20), the world reacts by setting drastic conditions for a sustainable development of the planet. In the six regions (see footnote 2), total food availability equals 3 000 kilocalories/capita/day in 2050. This slight increase in total calories from the 2 000 world average means a decrease in two regions (OECD and MENA), stagnation in two other regions (LAM and FSU) and an increase in the two last regions, that is Asia and Sub-Saharan Africa. Similarly, consuming 5 00 kilocalories/capita/day of animal products leads to a decrease in consumption levels in developed countries and an increase in developing countries, compared to base period levels. All in all, global needs in food calories are 30 % lower in the Agrimonde 1 scenario than in the Agrimonde GO scenario thanks to reduced food losses and waste from field to plate[5], and improved food diets. And even if global food availability is identical in all regions (in terms of total calories and calories from animal source), food diets are more diverse in Agrimonde 1 than in Agrimonde GO under the influence of several factors ranging from cultural, religious and ethical criteria to nutritional public policies.

What are the consequences of the Agrimonde 1 scenario for land use and crop yields? All in all, global food calorie needs in 2050 are 30% lower in Agrimonde 1 than in Agrimonde GO. This translates into increases in yields that are also significantly lower in Agrimonde 1 and allows managing agricultural land area in a markedly different way compared to Agrimonde GO. Local know-how and agro-ecosystem services are optimized. Innovation is both generic and specific. This process favors biological, ecological and technological choices based on the sustainable intensification of agricultural practices and systems that limit negative impacts on the environment: agricultural greenhouse gas emissions are cut, soil, air and water resources are better protected, biodiversity is enhanced. Yields rise in all regions but unevenly: increases are moderate in the OECD, Asia and MENA; they are more important in LAM, SSA and the FSU. Because increases in yields are modest, cultivated land surface expands considerably, much more than in Agrimonde GO, and this despite the

[3] This percentage sums up greenhouse gas emissions at the various stages of the livestock commodity chain. These stages include deforestation for pasture and feed crops, animal production, and the processing and transportation of animal products.

[4] For a summary of the first three analyses, see Grethe *et al.* (2011).

[5] In a general way, food waste and losses occur at the farm gate in developing countries, and at the distribution and final consumption stages in developed countries (and in richer households of emerging countries).

fact that global calorie needs are lower in Agrimonde 1 than in Agrimonde GO. But this increase in arable land occurs almost exclusively by conversion of pastureland in so far as forest cover remains practically constant. Finally, in both Agrimonde 1 and Agrimonde GO, increased local agricultural production is not sufficient to meet domestic needs in the three regions of MENA, SSA and Asia (these three importing regions represent a population of around 7 billion in 2050). This deficit is compensated by increased imports from the three other regions distinguished in the Agrimonde foresight study, that is LAM, the OECD and the FSU (these three exporting regions represents a population of around 2 billion people in 2050). International agricultural trade is more developed in Agrimonde 1 than in Agrimonde GO.

V. The land footprint of meat consumption worldwide: the role of plant yields, feeding efficiencies and international agricultural trade

The Agrimonde 1 foresight scenario shows that feeding the world in 2050 in a more sustainable way would be possible provided that consumption of animal products, notably meat, do not increase by large amounts, provided also that the world rise in the calorie intake remains limited, waste and losses are reduced along the whole food chain and non-food uses of agricultural biomass are controlled. Such an outcome would require that significant land area be devoted to agriculture at the world level. In addition, it implies a significant increase in international agricultural trade. These results directly relate to the joint issues of land availability and agricultural production location across the world. These issues are at the hearth of the on-going foresight exercise called Agrimonde-Terra which has been launched in the following of the first Agrimonde foresight study. First results of Agrimonde-Terra will be available on the beginning of 2016[6].

Agrimonde-Terra is interested in the same topic as Agrimonde, that is, in a general way, ‘’how to feed the world in 2050?’’. The focus is on land use and land use changes, and their interactions with food security at the household, regional and world level. Are there different ways of using available land worldwide? To what extent these different ways do contribute to ensure food security at various levels? What could be the impacts of climate change to this regards? These are the three main questions which drive the work. The latter includes both a qualitative (building of scenarios and development of their storylines) and quantitative (development of a quantitative platform - GlobAgri Agrimonde-Terra - and simulation of foresight scenarios) approach.

In this section, we present some preliminary results of the quantitative part of the work dealing more specifically with the role of livestock as regards land use and land use changes. Firstly, using the reference database of the Agrimonde-Terra foresight study, we emphasize that, behind aggregate or location-specific figures such those reported in previous sections of this paper, feed conversion ratios (or, equivalently, feed efficiency ratios) of livestock vary widely across species, regions and livestock systems. Secondly, using the balance sub-model of Agrimonde-Terra, we show how the land footprint of one kg of meat varies a lot in function of species and more importantly according to the world region where this kilogram is consumed. Thirdly, we illustrate the extent to which this land footprint is sensitive to feed efficiencies, plant yields and international agricultural trade.

The quantitative platform of Agrimonde-Terra is described in Appendix 1 (GlobAgri Agrimonde-Terra). Livestock feed conversion ratios per species, production regions and livestock systems have been computed using data from Herrero *et al.* (2013), Monfreda *et al.* (2010) and Bouwman *et al.* (2005)[7]. They include all ingredients used for feeding animals, including by-products and residues,

[6] For more details on the Agrimonde-Terra foresight study, see http://www.agrimonde.org.

[7] We warmly thank Mario Herrero and Petr Havlik for providing us with additional data relative to those reported in the supporting information of 2013 PNAS paper.

and in the case of ruminants, forage and grass whatever grown on temporary pastures or provided by permanent pastures.

5.1. Feed conversion ratios

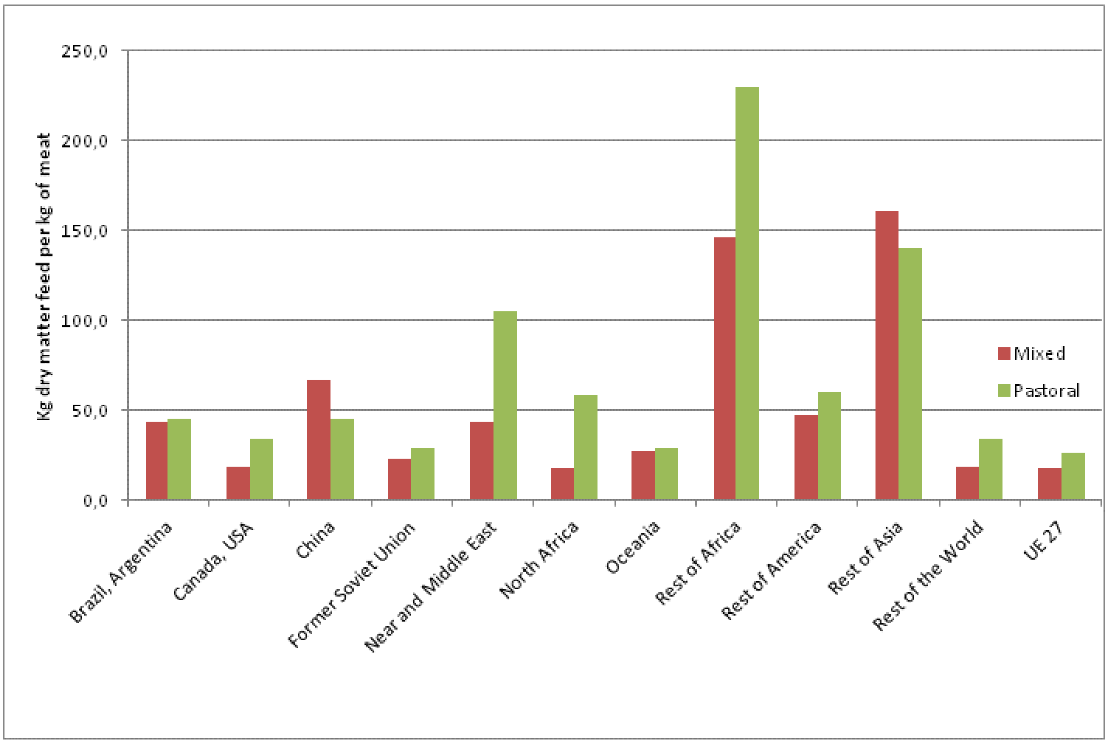
In a general way, feed conversion ratios are much higher for ruminants than for monogastrics (see Figure 5.1, panels 1.a and 1.b *versus* panels 1.c and 1.d). Within ruminants, they are most often higher for bovine than for ovine. Within monogastrics, they are higher for pork than for poultry. Also obvious from Figure 1 is the fact that feed conversion ratios vary widely according to geographical zones and for a given specie and a same region, in function of production system (pastoral *versus* mixed). This variability in feed conversion ratios results from differences in animal feeding efficiencies which themselves depend on the combined effects of animal genetics and breeding, feed ration composition (more grass-based *versus* more concentrate-based), livestock practices and natural conditions. As regards ruminant production systems for instance, panel 1.a for bovine meat and panel 1.b for small ruminant meat show that pastoral systems which rely more importantly on grass are most often less efficient in transforming feed into meat than mixed systems which are more based on concentrates and use less grass. However, within each livestock system (pastoral and mixed), the variability of feed conversion ratios across regions indicates that production conditions are highly heterogeneous. To this regards, Figure 5.1 suggests that the heterogeneity of feed conversion rates across the world is lower for monogastrics than for ruminants. This may be due, at least partly, to the fact that production of monogastric meat is mainly issued from industrialized livestock systems which are more standardized worldwide.

From panel 1.a, one notes that 1 kg of bovine meat may require more than 200 kg of dry matter feed when produced on a pastoral system in the region “Rest of Africa” but only 18 kg if produced by a mixed system in the European union (UE) or in North-America (Canada and USA). In the same way, 1kg of small ruminant meat may require more than 100kg of dry matter feed if produced by a pastoral system in the region “Rest of America” while less than 13 kg are needed for a mixed system in the EU (panel 1.b). As regards monogastrics, 1kg of pork meat requires more than 20 kg of dry matter feed in the region “Rest of Africa” and less than 5 kg in China (panel 1.c), and 1 kg of poultry meat requires as much as 16 kg of dry matter feed in the FSU while only 2 kg are needed when produced in China (panel 1.d).

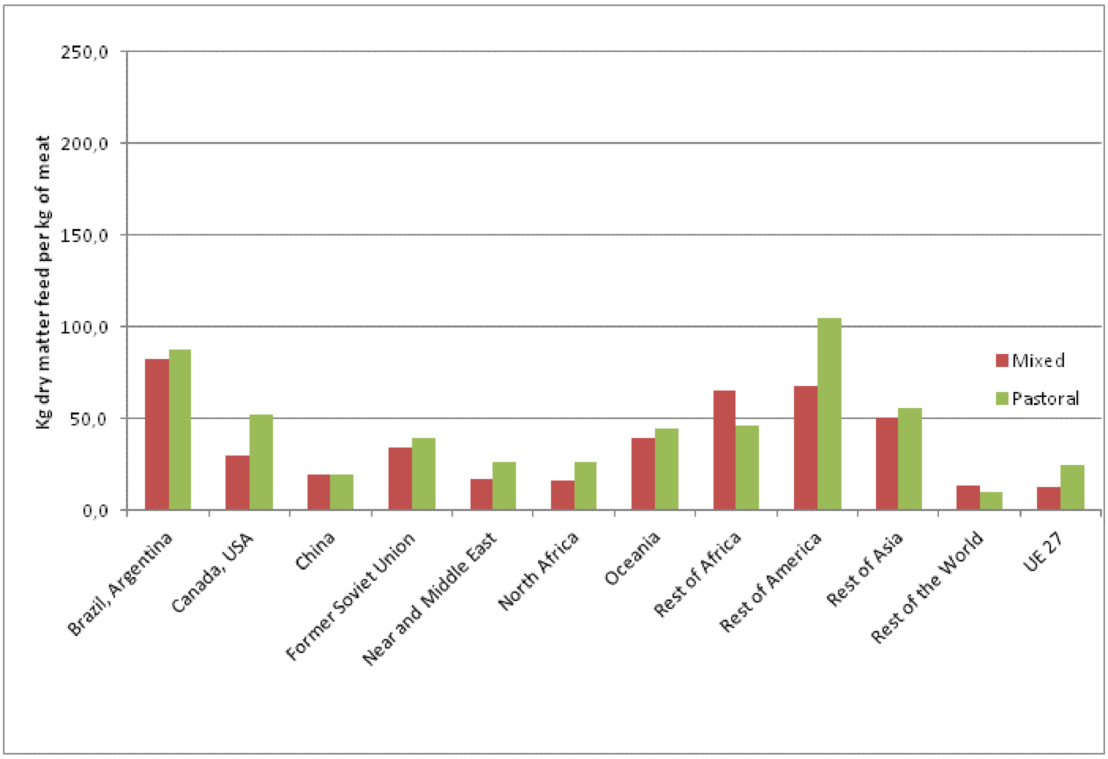
These figures may be questioned on various grounds directly linked to data availability and quality in many countries. They however suggest that there exist large efficiency gaps around the world within livestock systems, especially within ruminant systems. As a direct result, there exists flexibility for improving livestock efficiency in a large number of world regions.

Figure 5.1. Feed conversion ratios of meat livestock production in the different regions on the world, in kg of dry matter feed per kg of meat (all ingredients used for feeding, including by-products and residues, and for ruminants forage and grass)

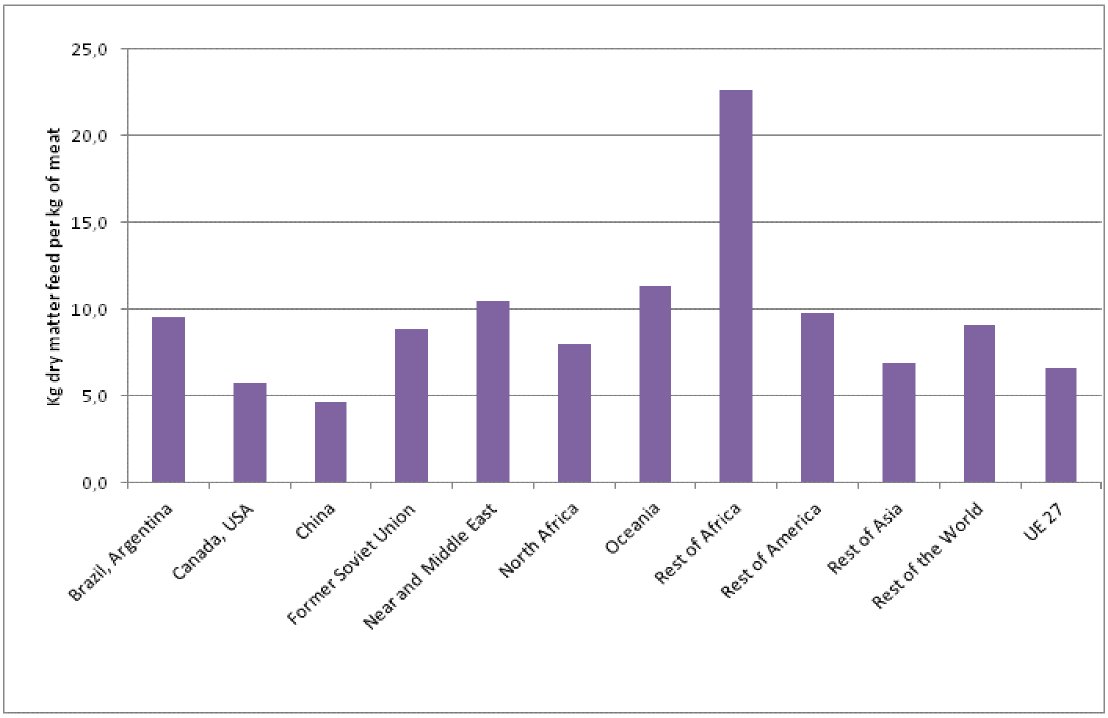
Panel 1.a. Bovine meat



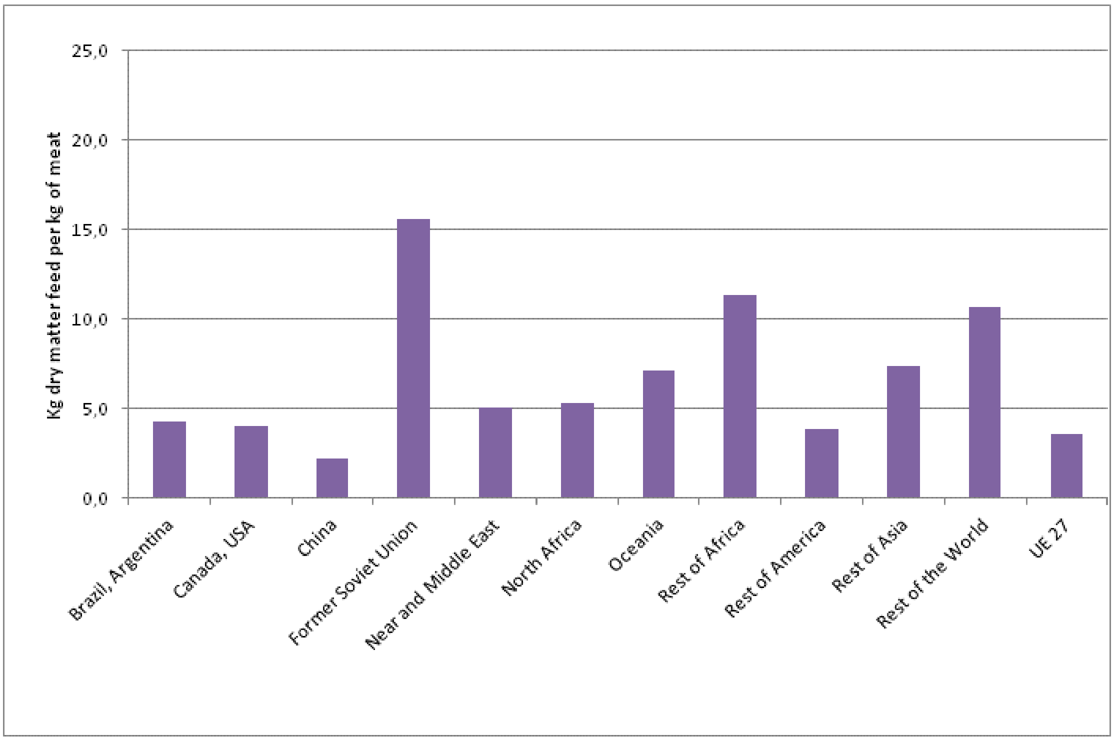
Panel 1.b. Small ruminant meat (sheep and goat)



Panel 1.c. Pork meat



Panel 1.d. Poultry meat



5.2. Land footprint of meat consumed in the various regions of the world

Feed conversion ratios are key elements as regards the land footprint of produced meat. The variability of these ratios across species, regions and production systems will translate into variability in land footprints of the various meats produced across the world. However these land footprints also depends on plant yields which similarly vary from one region to the other. On a general way, the lower the feed conversion ratio and the higher the plant yields, the lower the land footprint of produced meat.

In the following, we do not compute and analyze the land footprint of produced meat, but the land footprint of consumed meat. The difference between the two indicators lies in the fact that meat consumed in one region may have been produced in that region (the land footprint of consumed meat is then equal to that of produced meat) or may, at least partly, be imported from another region (in that case, the land footprint of consumed meat differs from that of produced meat, and the higher the gap between feed conversion ratios and plant yields between importing and exporting regions, the higher the differences between land footprints of produced *versus* consumed meat). As a result, dealing with the land footprint of consumed meat allows highlighting the role of agricultural trade as regards the use of land.

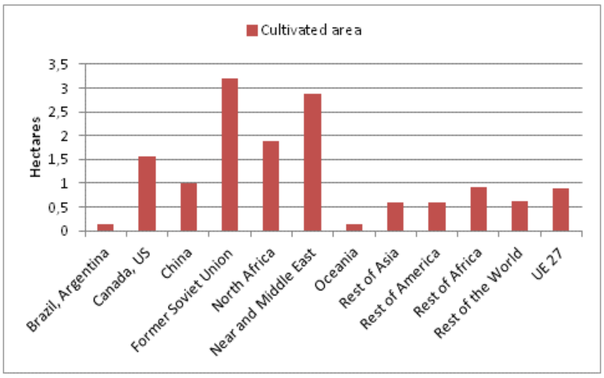
Figure 5.2 reports additional agricultural hectares (arable and permanent crops, as well as permanent pasture area) induced by a 1 ton food use increase of bovine meat (panel 2.a), small ruminant meat (panel 2.b.), pork (panel 2.c) and poultry (panel 2.d). Let us take the example of bovine meat in China to illustrate how to interpret these data. Panel 2.a indicates that 1 additional ton of bovine meat consumed in China requires around 54 supplementary hectares at the world level. These 54 supplementary hectares correspond to 1 supplementary hectare of arable and permanents crops and 53supplementary hectares of permanent pasture. These 54 supplementary hectares are partly located in China (increase in domestic production) and partly located in the rest of the world (increase in Chinese imports)[8].

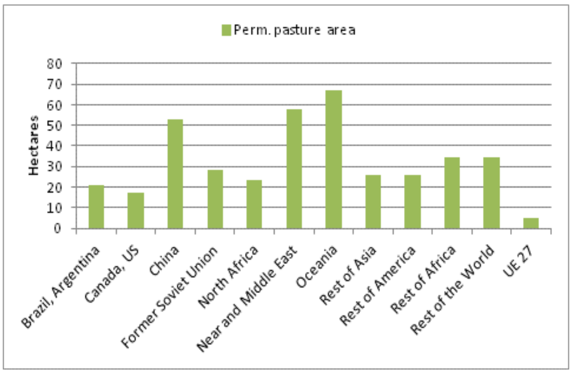
Figure 5.2 clearly shows that whatever the type of meat, increased consumption in different regions does require far different additional agricultural land area: 1 supplementary ton of consumed bovine meat requires from 6 additional hectares in the EU up to 67 additional hectares in Oceania; 1 supplementary ton of small ruminant meat requires from 20 additional hectares in the EU up to 97 additional hectares in Oceania; 1 supplementary ton of pork meat requires less than 1 additional hectare in China up to nearly 5 additional hectares in the region “Rest of Africa”; and 1 supplementary ton of poultry meat requires from 0.5 additional hectare in China up to 5 additional hectares in the FSU.

[8] For more details on the way domestic production and imports adjust following an increase in food use of a given meat, see Appendix 1.

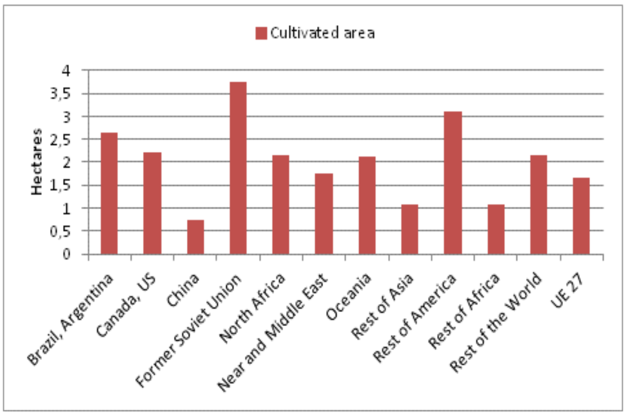
Figure 5.2. The land footprint of the various types of meat in the different regions of the world (number of hectare per additional tone of meat consumed in each region)

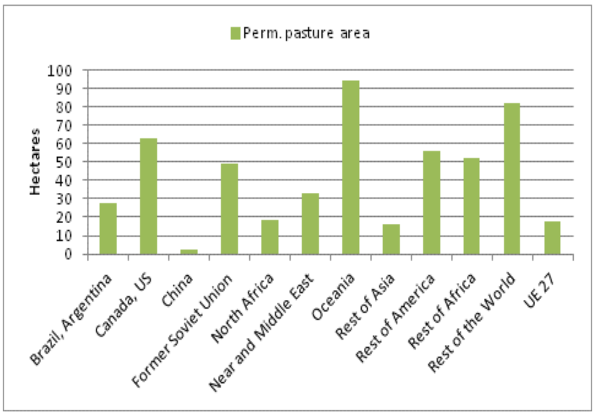
Panel 2.a. Bovine meat



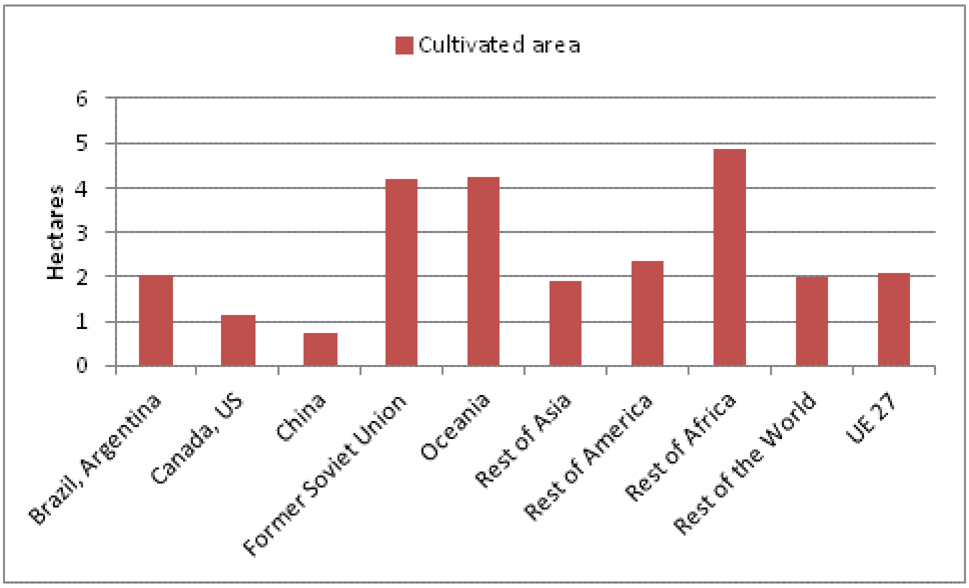


Panel 2.b. Small ruminant meat (sheep and goat)

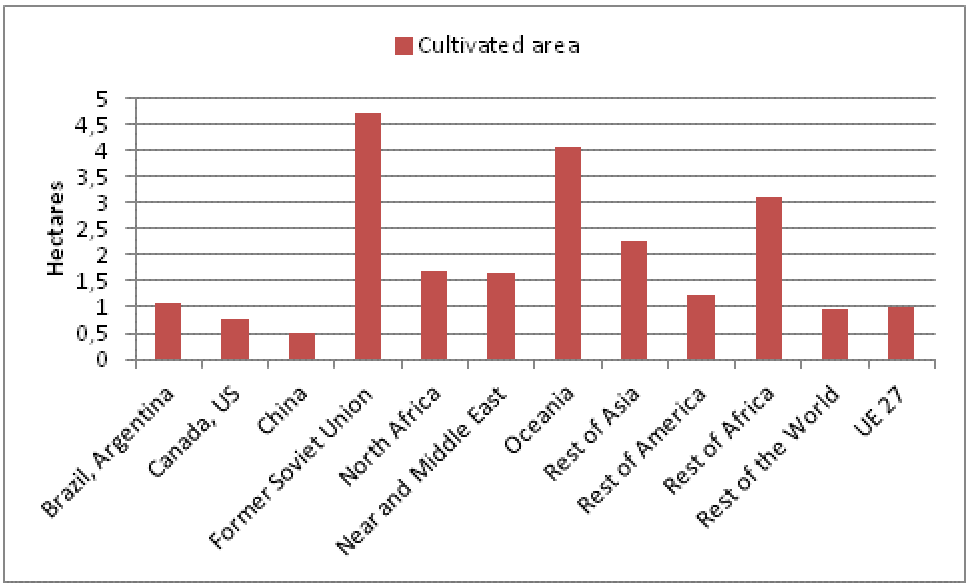




Panel 2.c. Pork meat



Panel 2.d. Poultry meat



What is clear from Figure 5.2 is that the various types of meat consumed around the world use far different land areas. Because of the extensive use of permanent pasture, ruminant meat requires substantially larger land areas than meat from monogastrics. However a large part of land recorded as permanent pasture in FAO data corresponds to marginal land without real alternative use. As a result, even if pork and poultry meat requires far less land than ruminant meat, the latter uses marginal and low quality land which would not be used otherwise, at least for agriculture.

5.3. Sensitivity analysis

Several levers could be used to decrease the land footprint of meat consumed worldwide. Among them, increasing yields of feed crops and rising livestock feeding efficiency appear as two main improvement ways. This is illustrated by Figure 5.3 for the specific case of pork meat in four regions (Canada and USA, China, Rest of Asia and the EU 27). The blue bar corresponds to the reference footprint calculated on the basis of historical data. From that starting situation, we evaluate the effects on an increase by + 0.3% in plant yields (red bar) and inversely, the effects on a decrease by - 0.3% in plant yields (green bar). We also depict the consequences of a decrease by - 0.3% in feed conversion ratios (purple bar) - this decrease corresponds to improved feeding efficiency

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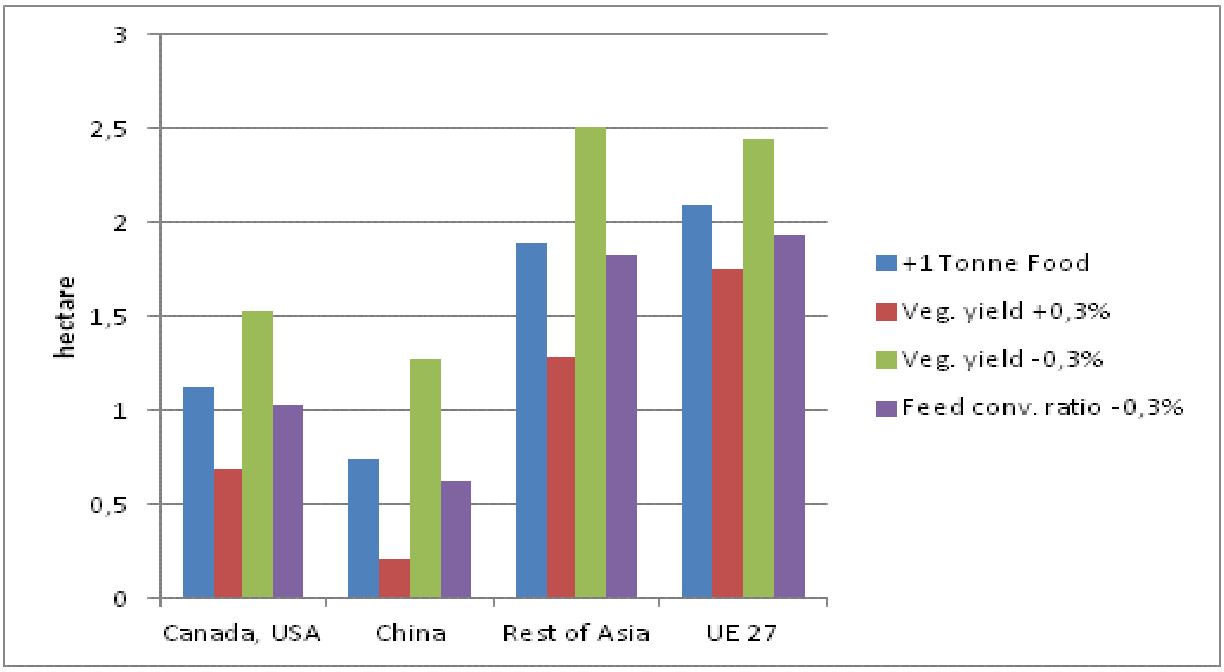
Figure 5.3. Sensitivity of the land footprint of pork meat consumed in selected regions (hectares per additional ton of meat consumed in each region)



Results displayed in Figure 5.3 suggest that plant yields are a powerful lever to reduce the land footprint of pork meat consumed worldwide. Increasing yields of feed ingredients by + 0.3% would reduce the land foot print of pork meat consumed in North America from 1.1 to 0.7 hectare (- 0.4 hectare); the decrease would be of the same order of magnitude in the EU 27 (from 2.1 to 1.7 hectare); it would be more important in China (from 0.7 to 0.2 hectare) as well as in the region ''Rest of Asia''. In a general way, the sensitivity of the land footprint to plant yields varies across regions, firstly because the composition of pork feed rations differs from one region to the other, secondly because the share of consumed meat which is imported from other regions (and thus does not benefit from improved plant yields in our sensitivity analysis) also differs between regions.

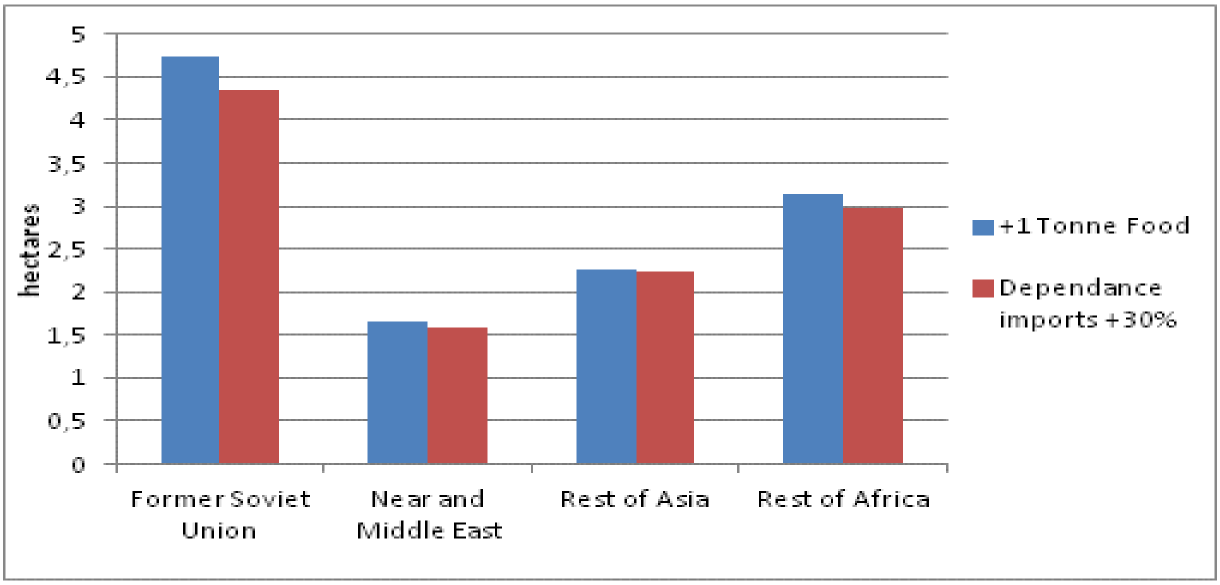
Even if increasing pig feeding efficiency would also help to save land, this second lever appears less powerful than increasing feed plant yields. This result is however specific to monogastric rations which do not rely on grass. In the case of ruminants, increasing feed efficiency would also allow to save pasture land and thus to significantly decrease the land footprint of ruminant meat consumed in each region.

International agricultural trade could also help to use farm land more efficiently. Because livestock systems are heterogeneous around the world, it is possible, at least theoretically, to reduce the land footprint of meat at the global level by producing more meat in the most efficient regions and substituting domestic production by imports in the least efficient regions. This point is illustrated by Figure 5.4 in the specific case of poultry meat. The cultivated land required for 1 additional ton of poultry meat consumed in the main importing regions (FSU, Near and Middle East, Rest of Asia and Rest of Africa) has been computed in two regimes corresponding to, respectively, (i) the benchmark situation (blue bar) and (ii) an hypothetical situation in which the dependence of poultry meat to imports is increased by + 30% (red bar)[9]. Results presented in Figure 5.4 show that international agricultural trade can effectively reduce the land footprint of poultry meat consumed worldwide, but

[9] In the GlobAgri Agrimonde-Terra model, the dependence to imports in a given region is calculated for each product as the ratio of imports on domestic use (product-specific import dependence ratio).

this effect is however of limited magnitude. In the FSU and the region ''Rest of Africa'', increasing the dependence import ratio of poultry meat by + 30% would allow reducing the land footprint of poultry meat consumption by, respectively, 0.4 hectare (from 4.7 to 4.3 hectares) and 0.3 hectare (from 3.1 to 2.9 hectares). In the two other importing regions (Near and Middle east and Rest of Asia), the land footprint would be reduced by less than 0.1 hectare.

Figure 5.4. Impact of international agricultural trade on the land footprint of poultry meat consumed in selected regions (hectares per additional ton of meat consumed in each region)



VI. Conclusion

Livestock production does not have to be definitively condemned because of its drawbacks that however should urgently and efficiently be addressed with the aim, notably, of reducing its land, energy and environment footprint. In the same way, consumption of animal products, notably meat, does not have to be definitively condemned on the basis of environmental and health arguments which does mean that consumption should not be reduced when it is excessive.

This issue concerns not only domestic animal production from local feedstuffs but also trade in animal products and feed ingredients. One interesting result of both the Agrimonde GO and Agrimonde 1 foresight scenarios is in effect that agricultural trade should increase over the next decades. As far as international trade is concerned, both scenarios end with the same image in 2050, that is a world divided into two groups of regions with one group (OECD, LAM and FSU) enjoying an agricultural surplus and supplying the three other regions with a deficit (Asia, MENA and SSA). This result raises the question of how to secure international agricultural trade and stabilize food prices. Trade, energetic and environmental policies should be closely linked which is unfortunately not the case today in the framework of international regulations on trade, climate change, biodiversity, *etc.*

On the other hand, it is worthwhile remembering that animal products are also an important source of proteins and easily absorbed minerals, trace elements and vitamins in many diets. For many poor and very poor households, the issue is to increase the consumption of animal products for improving their diet. In addition, livestock produces organic fertilizers, exploits land, notably marginal land that cannot be used for crops, is a safety net for many poor farm households in a context where prices of feed crops are more and more volatile, and conveys historical, cultural and religious values in many civilizations.

The westernization of eating patterns worldwide is a threat for global food security. Acting on eating patterns by reducing global food intake and proteins of animal source for countries and households where they are excessive may undoubtedly help to achieving world food security in 2050 and beyond. Acting on eating patterns alone and in particular reducing excessive consumption of animal products is however not sufficient because the global food challenge requires actions on both the demand and supply side.

On the food consumption side, the first priority is to reduce waste and losses at distribution and final consumption stages by increasing the use of raw materials for food and feed, by developing new transformation processes based on the concept of bio-refineries, and most importantly by improving our understanding of food consumption behaviors in order to induce desirable changes and define adapted public regulations. It will be also necessary to change current diets that are excessive and/or unbalanced and more generally, to reverse the global trend towards the westernization of eating patterns worldwide as the latter presents numerous shortcomings and drawbacks, notably in terms of health, impacts on the environment and use of natural resources. This does not mean setting up a common eating pattern for every part of mankind. Although eating patterns have tended to converge over the past decades, they remain diverse throughout the world and are determined by a complex set of physiological, economic, historical, cultural and sociological factors. This diversity should be exploited further to define healthier and more sustainable diets.

On the agricultural supply side, in addition to reducing post-harvest losses and strongly limiting the expansion of first-generation biofuels that use crops that can also be used for food (and feed !), it will be necessary to increase plant yields, especially in regions where they are currently low, and it will be necessary to do so in a sustainable way. To that end, agricultural practices and systems used worldwide should radically change. By construction, the more waste and losses will be reduced, the less the required increases in yields will be important. And the same argument holds for eating patterns and non-food use of agricultural biomass. This means that changing agricultural practices and systems alone is not sufficient. What is required is changing food systems, from plate to fork.

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Appendix1. The GlobAgri Agrimonde-Terra platform

The GlobAgri Agrimonde-Terra platform involves both a database and a biomass balance mode.

The database

The database uses FAO data, manly Commodity Balances (CB) data and, for some products, Supply-Utilization Accounts (SUA) data. One specific feature of the GlobAgri Agrimonde-Terra database is that for each CB product, the use the use classified as "processing" is allocated between food, feed and other uses after taking into account all final and derived products obtained from this processing amount[10].

The GlobAgri Agrimonde-Terra database covers 34 agricultural products, 25 plant products and 9 animal products. The world is divided in 14 regions, that is Brazil/Argentina, Canada/USA, China, Former Soviet Union (FSU), India, North Africa, Near and Middle East, Oceania, Rest of Asia, Rest of Africa, Rest of America, UE-27, West Africa and the Rest of the world.

For each CB product, total feed use is disaggregated among the various animal species (bovine, small ruminants, pork, poultry, aquatic products) and within species, to the different considered animal products (bovine meat, dairy, small ruminant meat, pork meat, poultry meat, eggs, aquatic products) and the different production systems (pastoral, mixed, urban and other for ruminants; urban and other for monogastrics). Once total feed has been disaggregated and allocated, corresponding feed conversion ratios are computed. This disaggregation process relies on data provided by Bouwman *et al.* (2005), Monfreda *et al.* (2008) and Herrero *et al.* (2013)[11].

The biomass balance model[12]

The model is composed of a balance equation for each product and each region:

$$Prod_{ijt} + Imp_{ijt} - Exp_{ijt} = Food_{ijt} + Feed_{ijt} + oth_{ijt} + Waste_{ijt} + VStock_{ijt}$$

where *i* denotes the product, *j* is the region, *t* is the reference year (2007-2009), *Prod* is the production volume, *Imp* are imports, *Exp* are exports, *Food* is food use, *Feed* is feed use, *Oth* are other uses, *Waste* are waste and losses, and *VStock* is the stock variation.

For vegetal products ($v \in i$), production equals the harvested area (A) times the per hectare yield (*Y*):

$$Prod_{vjt} = A_{vjt} * Y_{vjt}$$

For all products, feed use linearly depends on the production volume of animal products ($a \in i$):

$$Feed_{ijt} = \sum_{a} \beta_{iajt} * Prod_{ajt}$$

[10] For more details on this handling of the « processing » use of the FAO CB, see Dumas and Manceron (2014), GlobAgri database methodology. Agrimonde-Terra WP, 7 pages.

[11] For more details on the feed disaggregation, see Dumas (2014), GlobAgri: Disaggregation and re-aggregation of livestock data. Agrimonde-Terra WP, 8 pages.

[12] For more details on the biomass balance model, see Dumas and Guyomard (2014), The GlobAgri model. Agrimonde-Terra WP, 11 pages.

where β_{iajt} is the conversion coefficient of feed ingredient *i* for the animal product *a*, in region *j* and for year *t*.

For all products *i*, imports are defined as constant shares of total domestic use:

$$Imp_{ijt} = \alpha_{ijt}(Food_{ijt} + Feed_{ijt} + Oth_{ijt} + Waste_{ijt})$$

where α_{ijt} is the import dependence ratio for product *i* in region *j* for year *t*.

Exports are defined as constant shares of world market:

$$Exp_{ijt} = \sigma_{ijt} * (\sum_{j} Imp_{ijt})$$