Food Crops and Livestock:

From Worldwide Past Evidences (1961-2007) to Open Scenarios (2050)

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Abstract

Meeting the world demand growth in meat, milk and eggs requires increasing quantities of food crops to feed livestock. Feed/output ratios are known at local scales but not at national levels where heterogeneous breeding systems are coexisting. To fill this gap, we estimate over 47 years (1961-2007) with millions of FAO data how many calories and proteins of plant food products (*PFP*, mainly cereals and oilcakes, imported or locally produced) were used by countries for their animal food production (*AFP*). The empirical findings served to document and discuss the declining average productivities of *PFP* in *AFP* over the years, and to parameterize a simple model of livestock production that well simulate past evolutions in seven world regions. Results are also used to explore the need for food crops in 2050 according to five hypothetical scenarios of human diets ranging from “full veganism” to “full westernization”. Simulations show that plant food production should increase from 4 to 131% compared to 2007 while the population increases by 36%.

Key words: Food; Feed; Livestock; Calorie; Protein; Foresight

1. Introduction

Animal husbandry provides societies with a number of services and remains an integral and vital part of most farming systems around the globe (Dixon et al., 2001; FAO, 2009). Its expansion was rapid and important in recent decades due to an ever-increasing demand for animal foodstuffs (milk and milk products, meat, eggs, etc.) from human beings whose population doubled within 40 years (about 3 billion in 1960, 6 in 2000) and who tend to incorporate much more animal products in their diet when their standards of living improves.

This surge in demand for animal products led to devote growing areas of croplands and pastures to feed animals with cereals, oilcakes, roughages and other biomass, and to other problematic issues that are now serious subject of concerns especially in the environmental field (e.g. Bender, 1994; Brown, 1995; Rosegrant and Sombilla, 1997; Gerbens-Leenes and Nonhebel, 2002; MEA, 2005; Aiking et al., 2006; Steinfeld et al., 2006; McMichael et al., 2007; Fiala, 2008; Davidson, 2009; Friel et al., 2009; Glendining et al., 2009; Herrero et al., 2009; Stehfest et al., 2009; Popp et al., 2010; Vieux et al., 2012).

Continuation of past trends could indeed accelerates *(i)* the depletion of global carbon and biodiversity pools through the expansion of agricultural land and deforestation, *(ii)* the already high agricultural consumptions of freshwater, fertilizers, pesticides, antibiotics and fossil fuels that are used to boost crop yields and raise animals, *(iii)* the direct and indirect massive livestock emissions of methane and nitrous oxide, two powerful greenhouse gases. It could also increase food prices and food deficits of some countries, or the prevalence of epizootics or cardiovascular diseases. All in all, it challenges our ability to feed properly and in a sustainable way the whole human population expected in the future (likely 9 billion people in 2050).

Much more clarity is yet needed concerning livestock and the negative impacts they can have on greenhouse-gas emissions and the environment before technology and policy options can be studied and targeted appropriately (Thornton et al., 2009). One unclear aspect is the global relationship between food crops used as feed and corresponding livestock food production, the focus of this paper. This relationship is crucial for assessing many direct and indirect impacts of changing diets and livestock production, but it is still badly known at national scales because heterogeneous breeding farms coexist.

According to local resources, needs and prices, breeders are indeed combining in various proportions different food products or by-products (barley, maize, soya cake, roots and tubers, etc.) with different non-food biomasses (grass from pasture, fodder such as alfalfa, crop or food residues, etc.) to feed different kind of animals (calf, cow, buffalo, sheep, goat, pig, poultry, horse, etc.) that yield different foods (milk, meat, eggs, etc.) and other products or services (wool, manure, draft power, etc.).

To model livestock production and feed requirement, Seré and Steinfeld (1996) were the first to gather worldwide farm feed formulas to parameterize (for different regions and climatic conditions) few archetypes of livestock production, namely “grassland-based”, “mixed farming” and “intensive”. Their approach is now adopted in several global models, first in IMAGE which explores the long-term dynamics of global environmental change (Bouwman et al., 2005; Bouwman et al., 2006) (see Appendix A for more technical details). In other works, we use ourselves Bouwman et al.’s archetypes and feed coefficients to explore how could evolve extensive and intensive systems under different price scenarios (Souty et al., 2012).

Keyzer et al. (2005) also use this approach to show that international projections of feed requirements for 2030 are severely underestimated because they use a constant feed/meat ratio whereas it is likely to increase. They argue, with the following equation linking demand for concentrates C (feed from cereals, oilseeds and other marketable crops) and meat consumption M, that the residuals R (non-marketable inputs comprising crop residues and household waste) can no longer be regarded as a free input:

$$C = aM - R \tag{1}$$

"The challenge is to quantify the parameters of this relationship" and Keyzer et al. tried to do it for the cereals-meat relationship using Seré et al.'s archetypes of livestock production and farm feed/meat ratios that are inevitably based on time-dated, patchy and incomplete databases (Kruska et al., 2003).

The ambition of this paper is to quantify these parameters with solid historical evidences, not only for meat but for all animal food production (*AFP*) and with all plant food products used as feed (*PFP*). Our results show that above linear equation is a good form to report the (not constant but) increasing *PFP/AFP* ratio that we observe almost everywhere in the world from 1961 to 2007. We use these results to explore food crop requirements in 2050 according to five hypothetical scenarios of human diets.

The next section explains what data were used and how they were compiled to provide solid worldwide historical estimates of *AFP* and *PFP*. The following section presents and comments these historical estimates before providing modelling parameters for seven world regions. Last section exposes our scenario assumptions for 2050, the projection results and the main lessons drawn from them.

2. Global food balances in calories and proteins

The key insight of our work was to convert and aggregate into kilocalories (kcal) or proteins all plant food products (*PFP*) used by a country (or a region) to produce all its animal food products (*AFP*). This section describes briefly[1] how we proceed to provide and validate these new historical estimates with millions annual country FAO[2] data on production, trade and consumption, so that ratios could then be calculated to document and portray how have evolved feeding rates (*PFP*/*AFP*) or, conversely, *PFP* partial average productivities (*AFP*/*PFP*). We did that in three steps.

(a) Checking and merging of three international statistical series: "Commodity Balances" (CB), "Land"[3] and "Population" from FAO (2010) over 47 years (1961-2007) – Many islands or micro-states had to be removed because of missing or inconsistent data, and, for the same reason, Afghanistan, Iraq, Oman, Papua New Guinea and Somalia. Our final database, however, covers 98% of the world population (2000) and of the world land area (Antarctica excluded). Countries were grouped into seven world regions in this study: OECD country-members in 1990 (OECD), Latin America (LAM), Middle East and North Africa (MENA),

[1] For more details, see "Agribiom: a tool for scenario-building and hybrid modelling" in Paillard et al. (2011)
[2] Food and Agriculture Organization of the United Nations
[3] which includes *(i)* hectares of "arable" and "permanent" crops that we summed and called the "cultivated area"; cultivated lands include food crops but also some non-edible productions such as fibres, rubber, tobacco or fodders; *(ii)* hectares of "permanent meadows and pastures" that we named the "pasture area"

Sub-Saharan Africa (SSA), Former Soviet Union (FSU), Asia without China (ASIA-Ch) and China (Figure 1).

(b) Conversion into calories and proteins – All CB headings (“production”, “imports”, “exports”, “stock changes”, “food” uses, “feed” uses, “seed” uses, etc.) and CB lines of primary products used as food (from cereals grains to marine fishes) or edible in their primary form (from oilcakes to molasses) (Table 1) were converted from metric tonnes into food calories and the three macronutrients: carbohydrates, proteins and fats. These conversions over 109 product lines used the caloric, protein and fat contents of food provided by the FAO “for international use” (FAO, 2001: Annex 1), sometimes the USDA (2006). Carbohydrate contents were inferred assuming that they provide 4 kcal per gram (g) as for proteins while it is 9 for fats. In the case of oilcakes (e.g. soya bean cake) which have no food value for human beings, we inferred one with the food values of the seed or bean (e.g. soybean) and of the vegetable oil (8.84 $kcal.g^{-1}$ all from fat), and with the world average extraction rate of the oil (18% for soya bean).

(c) Aggregations and global equilibriums – Product lines converted into calories (and into their respective break-down into carbohydrates, proteins and fats) were aggregated into 5 compartments of food biomass: edible products coming from terrestrial plants (*VEGE*), from terrestrial grazing animals (*RUMI*) or non-grazing animals (*MONO*), from freshwater (*AQUA*) or sea water (*MARI*) (Table 1). During these aggregations, some headings were removed from calculations to avoid double or triple counting between “primary” products (e.g. oilseeds) and “processed” products (e.g. vegetable oils and oilcakes) of the CB, and to verify *in fine* the following equality for each country (*i*), year (*t*), biomass compartment (*b*) and metric (*m*: total calorie, carbohydrate, protein and fat):

$$PROD_{i,t,b,m} + IMPO_{i,t,b,m} - EXPO_{i,n,b,m} + STOC_{i,t,b,m} =$$

$$FOOD_{i,t,b,m} + FEED_{i,t,b,m} + SEED_{i,t,b,m} + OTHE_{i,t,b,m} + WAST_{i,t,b,m} \quad (2)$$

In above equation, utilizations in the form of food (*FOOD*), feed (*FEED*), seed[4] (*SEED*), waste (*WAST*) and other (*OTHE*) equals the supplies calculated as the domestic productions (*PROD*) increased or reduced by imports (*IMPO*), exports (*EXPO*) and stock variations (*STOC*).

These supplies-and-uses balances were achieved with our different metrics but not perfectly for plant foods ("leakages" below 2% except for the USA after 1980) for reasons detailed in Appendix B. They strongly legitimate our *PFP* estimates (the *FEED* heading of our *VEGE* compartment) and *AFP* estimates (the *PROD* heading of the *RUMI* and *MONO* compartments) since they proved to be coherent with millions of other national and international statistics, over 47 years.

3. Declining productivities of plant feed

Between 1961 and 2007, the human population has slightly more than doubled (+116%) but the gross world[5] production of food calories[6] increased by 183%[7] according our estimates. It reached the equivalent of 37,400 Gkcal.day^{-1} in 2007 with 62% of that energy provided by carbohydrates (2,155 Tg for the whole year), 24% by fats (368 Tg) and 14% by proteins (471 Tg).

[4] Or any other form used for reproductive purposes, such as eggs for hatching and fish for bait, whether domestically produced or imported.
[5] In this paper, "World" must be understood as the total of our Agribiom countries (Figure 1).
[6] Plant, animal and aquatic products combined, some serving in the production of others (e.g. animal feed).
[7] by 163% for carbohydrates, 198% for proteins and 243% for lipids

89% of the gross caloric production was of plant origin (*VEGE*) and 10% of animal origin (*RUMI+MONO*). The animal food production (*AFP*) was 3,855 Gkcal.day^{-1} in 2007 (73 Tg of proteins – see Figure 7 for 1961-2007 regional evolutions), with 2,290 from grazing animals (meat and milk from *RUMI*), 674 from poultry (meat and eggs) and 891 from pig meat (respectively, 40, 21 and 11 Tg of proteins).

The livestock was fed with food and non-food biomasses. In 2007, the plant food products used as feed (*PFP*) represented almost 33% of the total plant food production, i.e. 10,810 Gkcal.day^{-1} (192 Tg of plant proteins or 50% of the total production of plant proteins). At least one third of the cultivated area was therefore used to feed the livestock with plant foods, i.e. 489 million hectares out of 1,509.

Over 1961-2007, this “feed” acreage increased by 11% while the “pasture” land (including shrubs and savannahs) increased by 9% (3,268 Mha in 2007). All in all, total agricultural land for livestock (food crops and pastures) increased by 318 Mha (86% of the total increase in agricultural land over 1961-2007) and reached 3,758 Mha in 2007 (79% of the world agricultural area). It is a large figure but 87% are pasturelands that are not the best lands to crop while they are important reservoirs of carbon and biodiversity, even if less than forests.

Above figures show that 1 kcal of plant food (*PFP*) produced an average of 0.36 kcal of animal foodstuffs (*AFP*) in 2007. This (partial) productivity of the feed ranged between 0.50 in ASIA-Ch (the most efficient) and 0.22 in MENA (the less efficient). It varies from one region to another but also over years, as shown in Figure 3. When productivities are calculated with proteins, evolutions are more pronounced and the regional ranking changes as shown in Figure 4. Sub-Saharan Africa and Latin America become the most efficient while MENA remains the less. In what follows, we use the protein metric because it proved to yield more robust results in the models. Provision of proteins is also a key vocation of animal foodstuffs.

Figure 5 shows how average productivities decline when regional productions of animal proteins raise, except in China where it increased until 1999 (11 Tg). Several studies report substantial discrepancies in Chinese statistics (Keyzer et al., 2005; Rae et al., 2006) that may provide a first explanation. But China is also the region where the share of monogastric products (*MONO*) into total livestock production is by far the highest, and this share plays a role in feed productivities.

The share usually increases when the production of animal products increases, and Figure 6 shows how the feed productivity usually declines at the same time. The general story behind these evolutions is quite simple.

When land is rather abundant and the demand for animal products low due to low incomes, breeders are encouraged to raise grazing animals (mainly ruminants) to feed them as much as possible with “free” non-food biomass (pasture, shrubs, crop residues, etc.) to keep harvesting crops for human beings. They produce *AFP* with small quantities of *PFP* and the productivity of the latter (*AFP*/*PFP*) is all the greater than grazing animals provide in such low-income economies other important goods or services than food for rural communities (energy for traction, manure, wool, etc., not captured with *AFP*).

When population increases (lower abundance of land) and the demand for *AFP* increases, breeders are encouraged *(i)* either to increase the pasturelands as in Latin America, but it can be almost impossible as in Asia, *(ii)* or to crop (or import) *PFP* (of better nutritional values) and raise monogastric animals (pork and poultry) which are more efficient in converting *PFP* into *AFP*. As long as production costs of the latter are below *AFP* prices, hog and poultry farmers then grow along with *PFP*-"intensive" production systems for milk and beef. They all use larger quantities of *PFP* per unit of *AFP* compared to the "extensive" system described above. The overall *AFP* increases much but the *PFP* productivity tends to decline.

The story must of course be adjusted with local food preferences. In China for example, there is an ancestral preference for pork. The Chinese *PFP* productivity is therefore low compared to extensive-dominant systems, but is however higher than ever-increasing intensive-dominant systems elsewhere in the world. It may be due to constant efforts to improve it in a land-scarce environment, as in India but for milk production.

As shown elsewhere (Le Cotty and Dorin, 2012), we can model livestock production with a system of two-output (*AFP* from *RUMI* and from *MONO*) two-input (*PFP* and pasture acreages) cross-country production functions that can be then parameterized with our historical estimates and used to explore future global requirements of feed.

If we use a simpler model of livestock production (Equation 2) inverting the linear equation of Keyzer et al. (1), we get:

$$AFP = \alpha PFP + \beta \tag{2}$$

where α can be interpreted as the marginal productivity of *PFP* and β the quantity of *AFP* obtained without any *PFP*. The marginal productivity of *PFP* is fixed but not the average productivity which declines when *PFP* increases since:

$$AFP/PFP = \alpha + \beta/PFP \qquad (3)$$

With historical estimates of *PFP* in proteins, such a model proved to simulate robustly regional livestock productions of food proteins over the past half-century (Figure 7). It endogenizes declining feed productivities and concomitant increasing shares of monogastric productions. Table 2 gives the regional α and β estimates. The highest marginal productivities of *PFP* are in China (0.52) and Latin America (0.46) and the lowest in industrialized countries and MENA (≈ 0.25).

The model can be used to explore future requirements of feed. Then we return to the original equation of Keyzer et al. (1) but with our inputs:

$$PFP = \frac{1}{\alpha} AFP - \frac{\beta}{\alpha} \qquad (4)$$

In above equation, $1/\alpha$ is not the *PFP*/*AFP* ratio (or "cereal/meat ratio") as it could be understood from Keyzer et al., and β/α is not the quantity of "free" non-food biomass (herbs, crop residues, etc.).

The contribution of the "free" inputs to *AFP* can be assessed with equation 2 and our estimates. They contributed up to two-third of the animal production in sub-Saharan Africa in the early 1960s but it fell to 24% in 2007. It was still 40% in former Soviet Union and 24% in OECD in 2007 but no more than 12% in MENA and Latin America, and below 5% in Asia. With a higher demand for animal food products in the future, these shares should continue to decrease.

4. Scenarios of plant food requirement for 2050

Over 1961-2007, the world human population increased by 116% but the gross world production of food calories raised by 183% which enhances the average food availability per capita by 25%, including a 36% increase in animal calories. These growth rates are a bit lower than those calculated with official FAO's data[8] while our figures in calories are slightly higher: 2394 $kcal.day^{-1}$ in 1961 (against 2200 for FAO) and 3000 in 2007 (against 2796), with 369 and 503 respectively from (terrestrial) animal (against 338 and 481).

World averages mask large differences between regions. Table 4 ("REF" lines) shows how these differences are mainly explained by foods of animal origin whose per capita availability in 2007 reached almost 1190 $kcal.day^{-1}$ in OECD whereas it was below 150 in SSA.

By 2050, the world population will increase and the diets may move towards too opposite extremes: "westernization" (the historical trend) and "veganism". Full westernization and full veganism are both implausible economically but they bound the plausible futures. We use them to bound plant foods requirements in 2050 and the requirements of three intermediary scenarios. The five scenarios rely on various assumptions.

Regarding future human populations, we use the "medium fertility" projections of the United Nation (2012): 8,915 million capita (Mcap) in 2050 with countries shown on Figure 1 (9,405 in 2100) while it could range between 7,765 (low fertility) and 10,425 (constant fertility).

[8] "World+" average as on April 2012

World and regional projections (Table 3) are the same in all scenarios to facilitate their comparison.

Regarding diets, we test the five following scenarios:

- “diets of 2007” (REF) with 2050 populations,
- “full veganism” (VEG) with no consumption of animal foodstuffs everywhere in the world,
- “Agrimonde 1” (AG1), the “normative scenario” of our Agrimonde foresight (Paillard et al., 2011),
- “Agrimonde GO” (AGO), the “trend scenario” of the same collective foresight, based on the “Global Orchestration” scenario of the MEA (2005),
- “full westernization” (WST) with a typical western diet extended to the whole world.

Table 4 shows, for each scenario, assumptions regarding total regional availabilities per capita and the breakdowns into calories from plant, animal and aquatic origins.

Food of animal origin (*AFP*) is assumed to be produced with plant food only (*PFP*) after the reference year 2007 (and food of aquatic origin with aquatic resources only). Trade between regions is maintained at the level of 2007 after having adjusted it in such a way that all regional stock variations and statistical discrepancies are equal to zero (as in the scenarios). Supplies-and-uses balance of the reference year 2007 was recalculated so that other uses (such as biofuels) than seed, food, feed and wastes are equal to zero (as in the scenarios). Requirements in “seed” are assumed to represent 2.6% of regional food productions for plants and 0.4% for animals, the 2007 world averages. Similarly, post-harvest wastes are assumed to represent everywhere 3.8% of regional consumptions for plants and 1.2% for animals.

Regarding the requirements of plant feed (*PFP*) for producing animal foodstuffs (*AFP*), we test two modelling forms. The first is the linear form presented in the previous section and its regional parameters based on historical evolutions over 47 years (Table 2). In this first technical scenario (TS1) where past regional production functions are assumed to be the same in the future, simulations are done in proteins and upstream/downstream conversions into calories use the regional rates observed in 2007 (Figure 8, Figure 9)[9].

The second modelling form is a Cobb-Douglas form whose parameters are estimated only with OECD's historical data (in Gg.year^{-1} of proteins), giving ($R^2 = 0.99$):

$$AFP = 2.1421 \bullet PFP^{0.7196} \tag{5}$$

In technical scenario 2 (TS2), the above model is applied to all regions and the contribution of proteins to energy in *PFP* and *AFP* is assumed to be 20% everywhere (more or less the world average in 2007).

Figure 10 shows how the TS2 model fits rather well past evolution of Latin America and the one of China after 1995 but overestimates all other regional past productions of *AFP*. In the future however, the figure also shows how it will revise upward TS1 regional projections of feed requirement. In TS1, average productivities of *PFP* decline but not marginal productivities which may be lower in the future with higher production of *AFP*. In TS2, the marginal productivity of *PFP* declines when the production of *AFP* increases and all regions are assumed to produce *AFP* as in OECD. TS2 is therefore more pessimistic than TS1 regarding *PFP* requirement but is far to be the worst scenario: projections of *PFP* requirements would be higher if parameters of above equation were estimated with LAM, FSU, SSA or (worst) MENA historical data.

[9] Our working unit, the protein, actually led to endogenize the important change in feeding practices that occurred during the second half of the 20th century when oilcakes (in particular soya bean cake) increasingly became a protein complement.

The results of the scenarios are detailed in Table 5 and summarized in three figures (Figure 11, Figure 12, Figure 13). They show that *PFP* requirements in 2050 depend largely on future diets. Compared to 2007, the world consumption (or production) of plant food should increase by 4% with “full veganism” (VEG) up to 110% (TS1) or 131% (TS2) with “full westernization” (WST) whereas the world human population increases by 36%.

In all scenarios (except AGO-TS2), Sub-Saharan Africa is the region where the consumption of plant food should increase the most (up to 524% with WST-TS1[10]) due to a 126% increase in population. It is followed by Asia (excluding China) with a 40% increase in population. These two regions should represent between 40% (REF) to 59% (WST-ST2) of plant food consumption in 2050 while it was 32% in 2007. Conversely, the share of China should decrease from 19% in 2007 to 12-16% due to a slight decrease in population, and that of OECD from 26% in 2007 to 13% (VEG) or 24% (REF) depending on diet scenarios in 2050.

If OECD diets are lighter in meat and milk products than today, the region may strengthen in 2050 its net exports of food to the rest of the world, especially to Africa and Asia where food consumption should increase the most. Africa, the Middle East and Asia are already net importers of plant food in 2007 (Dorin, 2011). If they boost their exports of other goods and services, they should become much larger importers of food in 2050 unless a very large increase in their agricultural lands and/or yields is sufficient to meet the coming deficits. It may be partly possible in Africa but very hard in Asia where the land expansion is almost impossible and the yields already very high (Dorin, 2011).

[10] TS1 and not TS2 because assumptions on protein contents in *FFP* and *AFP* play also a role, especially with SSA where they are the most different between the two scenarios: 28.3% and 14.7% respectively in TS1, 20% and 20% in TS2.

The former Soviet Union may also increase its net exports of food in 2050 since it has an untapped reservoir of agricultural growth while its future food needs decrease in almost all scenarios. It is difficult to draw such a conclusion for Latin America. It has become an important and growing net food exporter since the mid-1990s but in 2050, it may also have to increase its production above 55% to meet the domestic demand in AGO or WST scenarios.

The results also show that TS1 and TS2 simulations doesn't yield important differences at the global and regional levels (Africa excepted) up to AG1 scenarios, i.e. when the livestock production in 2050 doesn't have to increase (or very slightly) compared to 2007. Conversely, in AGO and WST scenarios, the global livestock production of food has to more than double and our TS1 and TS2 models yield very different results at the regional levels (except for Latin America and OECD) for reasons discussed previously. Models of livestock production are obviously central in any international long term projection of food requirement and should be clearly presented with their assumptions before showing any results.

Regional differences between REF and AG1 scenarios go however beyond livestock modelling issues. In both scenarios, global plant food production in 2050 should increase by about 30% compared to 2007. In the REF scenario, current regional large differences in consumption of livestock products are maintained whereas there are levelled in AG1. The latter scenario may look completely unrealistic. Its benefits on human health would yet be very important in developing as well as in developed countries. Imaging such a hypothetical scenario could also lead to imagine other ways to intensify crop and livestock productions in the future in order to mitigate their ecological footprints. Our Agrimonde foresight (Paillard et al., 2011) investigates further this scenario, including its limitations and the pending questions.

5. Conclusion

Production and consumption of animal foodstuffs have emerged as a central subject of sustainable development. This study focused on the relationship between feed and livestock food production at national and global scales for two reasons: *(i)* modelling this relationship is of great importance for assessing many direct and indirect impacts of changing diets and livestock production, *(ii)* current international long-term projections face difficulties to represent this relationship at aggregated geographical scales due to numerous outputs (milk, beef, pork, sheep, goat, poultry, eggs, etc.), farming systems and feeding practices, which range from pastoralism or scavenging to highly specialized industrial farms.

To precise the relationship with historical evidences, we estimated over 47 years (1961-2007) with millions of FAO data how many calories and proteins of plant food products (*PFP*) were used by countries for their animal food production (*AFP*). The empirical findings served to document and discuss the declining average productivities of *PFP* in *AFP* over the years, and to parameterize a simple model of livestock production that well simulate past regional evolutions.

The results were also used to explore the need for food crops in 2050 according to five hypothetical scenarios of human diets ranging from “full veganism” to “full westernization”. Simulations showed that plant food production should increase from 4 to 131% compared to 2007 while the population should increase by 36%. They highlight how diets play a key role in sustainable development. They also show that model of livestock production are central in any international long term projection of food requirement; before showing their results, they should be clearly presented with their data and assumptions especially regarding marginal productivities of *PFP* in *AFP* (levels and trends, declining or not).

Our work can help to explore and debate direct and indirect future consequences of current trends in livestock sector and possible alternative developments. It also calls for improvements. It relies on solid worldwide historical estimates of *AFP* and *PFP* in calories and proteins but many other information are missing for modelling and thinking future regional economies of livestock production.

National and international statistical systems should pay a much greater attention not only to the non-food biomass used (or that can be used) for feeding animals, from permanent pastures and annual fodder to crop or food residues[11], but also to other important factors such as human labour and savoir-faire, capital and energy used for boosting the production and its quality, ecological performances of specialized and mixed farming systems, other services than food provision (draft, manure, saving, wool, leather or else), without forgetting local cultural preferences and religious taboos.

[11] to strengthen and extend the work of Séré and Steinfeld (1996), Devendra and Sevilla (2002), Wirsenius (2003), Bouwman et al. (2005), Smeets et al. (2007) or Krausmann et al. (2008)

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<u>Appendix A</u> – Modelling of animal production in the IMAGE model

L. Bouwman and colleagues (Bouwman et al., 2005; Bouwman et al., 2006) provide a model of livestock production which relies on expertises and data provided by Séré and Steinfeld (1996) for the period 1991-93 (sometimes 1981-83) at the level of 7 geo-economical regions (Sub-Saharan Africa, Asia, etc.) which Kruska et al. (2003) developped and mapped for the developing world. Bouwman *et al.* divide breeding activities into two aggregated production systems: "Pastoral systems" depending almost exclusively on grazing, and "mixed and landless systems" relying on a mix of concentrates (food crops) and roughage (grass, fodder crops, crop residues…). These two systems comprise groups of animals ("beef cattle" including meat from buffaloes, "dairy cattle", "sheep and goats", "Poultry" meat and eggs) which population are estimated for each system in each regions (24 regions in IMAGE 2.4) along with their typical production characteristics (milk production per animal, off-take rates for slaughter, carcass weights) in order to compute regional productions of milk and meat. Animal populations and typical production characteristics are also used by Bouwman *et al.* to estimate the volume of feedstuffs required for each regional production of milk and meat. To this end, they start calculating net energy animal requirements (MJ head^{-1} day^{-1}) for daily maintenance, grazing and labour, pregnancy and lactation. This calculation calls for additional assumptions, such as on maintenance energy per unit of body weight, time spent in pastures, milk fat content, weight of the calf at birth, fraction of animals that give birth, gestation period, etc. In a final step, in order to estimate volumes of various feedstuffs consumed to meet these energy requirements, sources of feed are divided into five categories: (*i*) grass including hay and silage grass, (*ii*) food crops and by-products (such as cakes), (*iii*) crop residues and fodder crops, (*iv*) animal products, (*v*) scavenging, including road-side grazing, household wastes, feedstuffs from backyard farming. It is then assumed that these feedstuffs have specific characteristics (dry matter and energy content, fraction digestible energy of total energy) and that they are consumed at fixed and specific proportions by each animal category and production system in each region. Since this proportion is itself dependent on the density of ruminants per hectare of grassland, additional assumptions are made on the number of animals and the area of grassland in each system, as well as on the productivity of the grasslands.

Appendix B – Supplies-and-uses balances

Supplies-and-uses balances in total calories, carbohydrates, proteins and fats are far from evident for several reasons, especially the following ones.

(*i*) Commodity Balances (CB) in tonnes (about 8.5 million values over 1961-2007) do not systematically verify line-by-line the equality between supplies and utilizations[12].

(*ii*) Similarly, for some commodities and years, the sum of all exports at the global level does not systematically equal the sum of all imports, the former usually exceeding the latter. These differences can be explained by the removal from our dataset of some countries which are most probably net food importers. But this possible explanation is obviously not the only one.

(*iii*) For some product-lines (e.g. sugar crops or oilseeds), the CB include the heading "Processing" into other CB product-lines which, according to the FAO, "could not be converted back to their originating primary commodities or which are part of separate food groups" (sugars, fats, oils and oilcakes, alcoholic beverages, etc.). These "processed" quantities had to be removed from our accounts along with the production of the "processed"

[12] As pointed out by the FAO, "there are many gaps particularly in the statistics of utilization for non-food purposes, such as feed, seed and manufacture, as well as in those of farm, commercial and even government stocks".

products[13] whereas we did not know precisely which, or even how, "primary" products were converted into "processed" ones[14] and therefore if the CB system includes important biomass "leakages" or not.

These problems led us to remove sugar cane and sugar beet lines from our dataset[15] and to consider sugars and molasses as "primary" products. The final picture obtained for plant food[16] can be shown at the level of our seven world regions (Figure 2). We see minor and rather constant biomass "leakages" between supplies and uses, except for the USA (in OECD) after 1980 (leakage above 2%).

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[13] Indeed, at a national level, these "processed" products are produced with previously accounted quantities of "primary" products, whether through their domestic productions and/or their imports.

[14] All the more so as we have quite complex cases such as alcoholic beverages, manufactured with "primary" items such as "grapes", as well as "processed" items such as "sugar" made from sugar cane and/or sugar beet.

[15] While sugarcane, for instance, can be used for feeding livestock in a country such as China.

[16] Supplies and utilizations are almost balanced for our other biomass compartments.

Tables

Table 1. Scope and compartmentalisation of edible biomasses

Group	Compartments	Products lines of FAO's Commodity Balances
Plant products	*VEGE*	Wheat, rice & other grains of cereals; Bran; Maize & rice bran oils Beans, peas & other pulses Cassava, potatoes & other roots or tubers Tomatoes, onions & other vegetables; Apple, oranges & other fruit Soya bean, cottonseeds, olives & other oilseeds or tree nuts with their by-products (oils, cakes) Sugars & molasses; Wine, beer & other; Cocoa, coffee & tea; Pepper, cloves & other spices
Animal products (*terrestrial*)	*RUMI* (grazing)	Bovine meat, mutton, goat meat & other meat; Edible offal; Meat meal Milk (excl butter), butter, ghee, cream Raw animal fat
	MONO	Eggs, pig meat, poultry meat
Aquatic products	*AQUA*	Freshwater fish
	MARI	Demersal fish, pelagic fish & other marine fish with their by products (oils, meals) Crustaceans, cephalopods & other molluscs, aquatic meat & plants

Table 2. Parameter estimation for regional linear models of livestock production
with input (*PFP*) and output (*AFP*) in Tg.year^{-1} of proteins

Region	α	β	R²	P value (Pr > F)
OECD	0.241786	6,689,256	0.985	< 0.0001
FSU	0.254921	1,781,576	0.941	< 0.0001
MENA	0.260066	383,616	0.995	< 0.0001
ASIA-Ch	0.402486	521,709	0.996	< 0.0001
SSA	0.411549	695,519	0.972	< 0.0001
LAM	0.459574	1,231,804	0.988	< 0.0001
China	0.524383	-2,177,900	0.966	< 0.0001

Table 3. Human populations (2007, 2050)
in 1000 capita

	World	ASIA-ch	China	FSU	LAM	MENA	OECD	SSA
2007	6,566,750	2,181,711	1,336,551	277,041	561,328	398,525	1,022,640	788,954
2050	8,914,966	3,060,948	1,325,889	272,419	742,192	591,027	1,137,700	1,784,791
2007-50	+36%	+40%	-1%	-2%	+32%	+48%	+11%	+126%

Table 4. Food availabilities (2007, 2050)
in kcal.day^{-1}.capita^{-1}

		World	ASIA-ch	China	FSU	LAM	MENA	OECD	SSA
REF	Total	3,000	2,512	3,096	3,517	3,170	3,402	3,949	2,452
(2007)	- vegetal	2,468	2,263	2,473	2,758	2,514	3,009	2,720	2,290
	- animal	503	226	574	733	640	375	1,186	147
VEG	Total	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	- vegetal	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	- animal	0	0	0	0	0	0	0	0
AG1	Total	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	- vegetal	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500
	- animal	450	450	450	450	450	450	450	450
AGO	Total	3,586	3,703	3,703	3,457	3,698	3,457	4,099	2,987
	- vegetal	2,691	2,766	2,766	2,091	2,758	2,987	2,385	2,667
	- animal	836	871	871	1,296	892	442	1,628	283
WST	Total	3,800	3,800	3,800	3,800	3,800	3,800	3,800	3,800
	- vegetal	2,650	2,650	2,650	2,650	2,650	2,650	2,650	2,650
	- animal	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100

Table 5. Consumption of plant and animal calories (2007, 2050)
in $Gkcal.day^{-1}$, seed and waste included

		World	ASIA-ch	China	FSU	LAM	MENA	OECD	SSA
REF	Animal	3,537	548	781	233	385	165	1,304	120
2007	- food	3,301	492	768	203	359	149	1,213	116
	Vegetal	27,413	6,407	5,295	1,564	2,591	1,970	7,220	2,365
	- food	16,206	4,937	3,306	764	1,411	1,199	2,781	1,807
	- feed	9,426	1,047	1,695	583	974	616	4,170	344
VEG	Animal	186	40	2	30	16	11	83	3
2050	- food	0	0	0	0	0	0	0	0
	Vegetal	28,574	9,824	4,232	876	2,410	1,870	3,651	5,710
	- food	26,745	9,183	3,978	817	2,227	1,773	3,413	5,354
	- feed	0	0	0	0	0	0	0	0
	- 2007-50	+4%	+53%	-20%	-44%	-7%	-5%	-49%	+141%
REF	Animal	4,205	742	778	232	498	236	1,452	269
2050	- food	3,960	691	762	200	475	222	1,349	263
	Vegetal	35,879	8,972	5,291	1,423	3,406	2,922	8,401	5,465
	- food	21,785	6,927	3,279	751	1,866	1,779	3,094	4,088
TS1	- feed	11,798	1,458	1,689	577	1,293	979	4,765	1,037
	- 2007-50	+31%	+40%	0%	-9%	+31%	+48%	+16%	+131%
TS2	- feed	10,748	1,712	1,827	304	1,056	309	5,145	396
	- 2007-50	+27%	+44%	+3%	-28%	+22%	+12%	+22%	+102%
AG1	Animal	4,258	1,440	610	154	355	281	601	818
2050	- food	4,012	1,377	597	123	334	266	512	803
	Vegetal	36,128	11,333	4,980	925	2,960	2,846	4,479	8,604
	- food	22,287	7,652	3,315	681	1,855	1,478	2,844	4,462
TS1	- feed	11,528	2,944	1,363	182	886	1,209	1,344	3,602
	- 2007-50	+32%	+77%	-6%	-41%	+14%	+44%	-38%	+264%
TS2	- feed	10,674	4,416	1,284	156	664	406	1,749	2,000
	- 2007-50	+28%	+101%	-8%	-43%	+5%	+1%	-32%	+191%
AGO	Animal	7,757	2,749	1,178	388	688	276	1,963	515
2050	- food	7,455	2,666	1,155	353	662	261	1,852	505
	Vegetal	48,689	15,181	6,534	2,067	4,179	3,127	10,188	7,412
	- food	23,989	8,467	3,667	570	2,047	1,765	2,713	4,760
TS1	- feed	21,583	5,731	2,465	1,362	1,836	1,185	6,819	2,188
	- 2007-50	+78%	+137%	+23%	+32%	+61%	+59%	+41%	+213%
TS2	- feed	25,643	10,993	3,311	666	1,648	395	7,601	1,031
	- 2007-50	+93%	+225%	+40%	-15%	+54%	+16%	+53%	+161%
WST	Animal	10,147	3,462	1,486	334	845	671	1,352	1,997
2050	- food	9,806	3,367	1,458	300	816	650	1,251	1,963
	Vegetal	57,669	16,421	7,010	1,938	4,572	5,069	7,889	14,770
	- food	23,625	8,112	3,514	722	1,967	1,566	3,015	4,730
TS1	- feed	30,354	7,247	3,064	1,089	2,283	3,201	4,365	9,105
	- 2007-50	+110%	+156%	+32%	+24%	+76%	+157%	+9%	+524%
TS2	- feed	35,746	15,185	4,610	531	2,187	1,483	4,699	7,053
	- 2007-50	+131%	+289%	+64%	-14%	+72%	+64%	+14%	+432%

Figures

Figure 1. Map of countries and world regions
Cartographic source: Articque

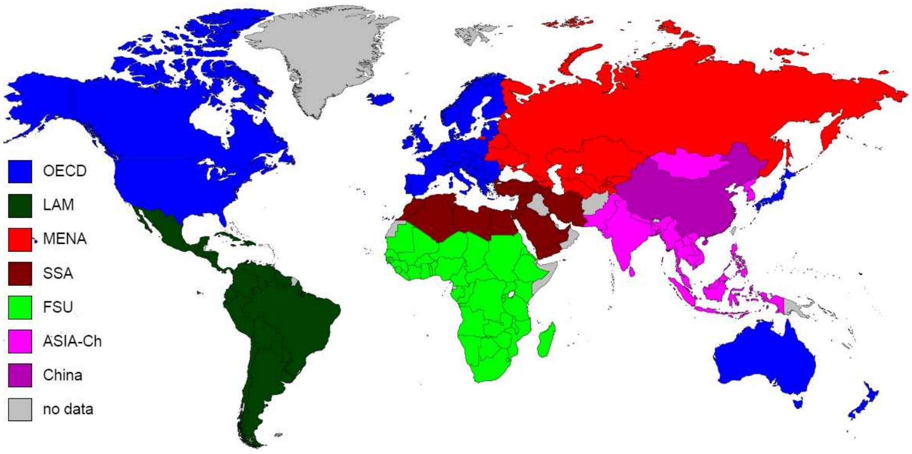

Figure 2. Difference between supplies and utilizations of plant food calories (1961-2007)

(total supplies – total uses) / total supplies

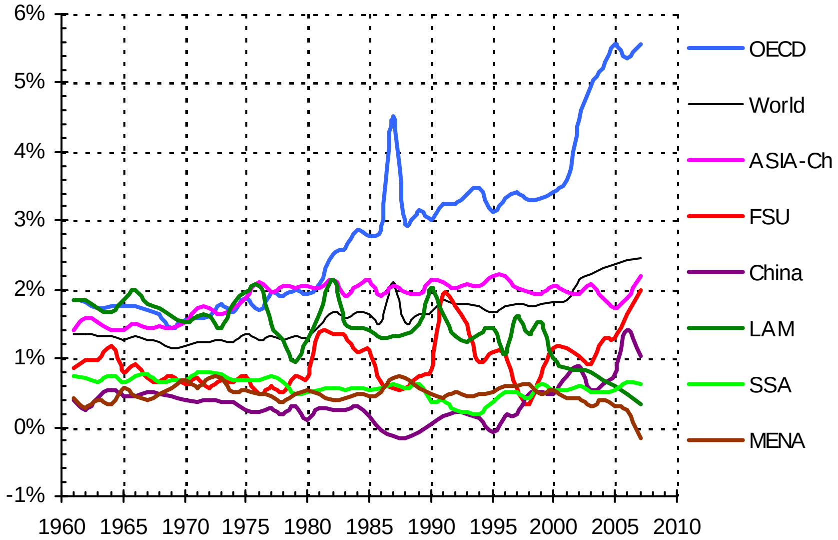

Figure 3. Caloric productivity of *PFP* (1961-2007)

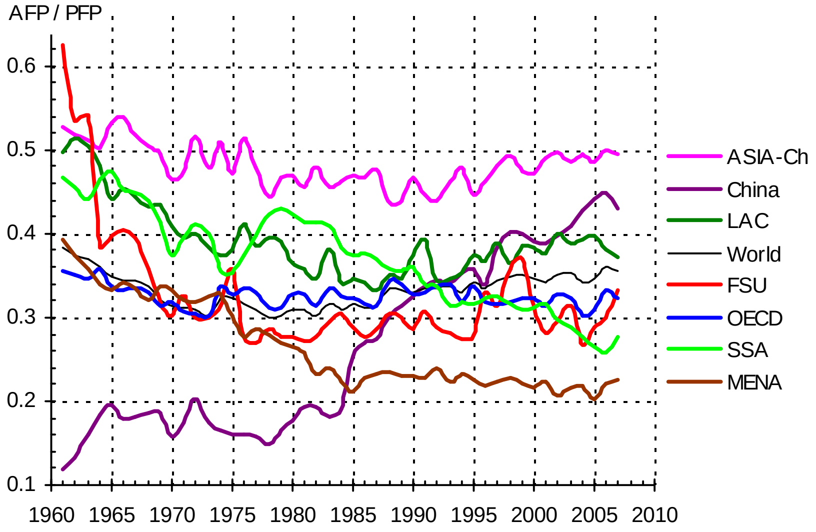

Figure 4. Protein productivity of *PFP* (1961-2007)

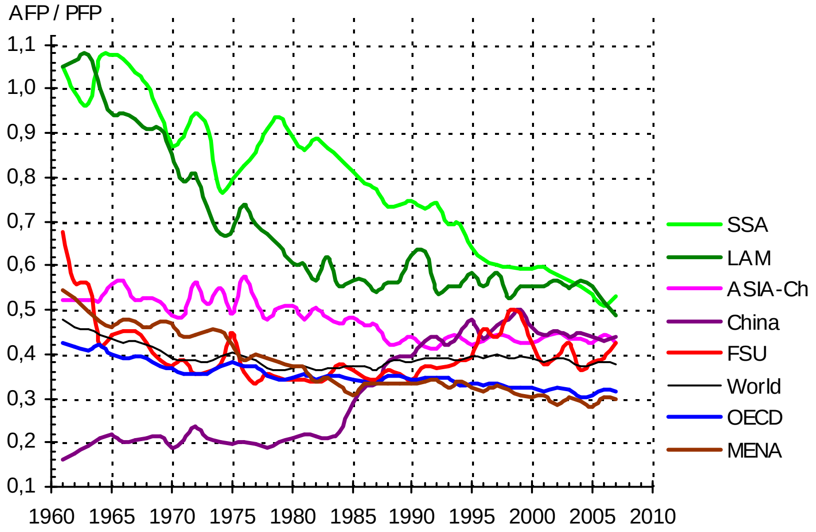

Figure 5. *AFP* and protein productivity of *PFP* (1961-2007)

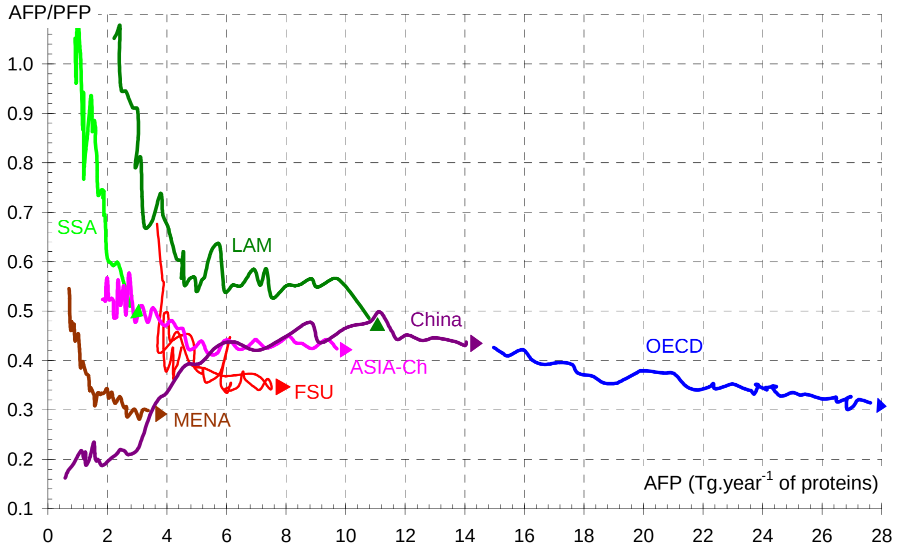

Figure 6. Monogastric share in *AFP* and protein productivity of *PFP* (1961-2007)

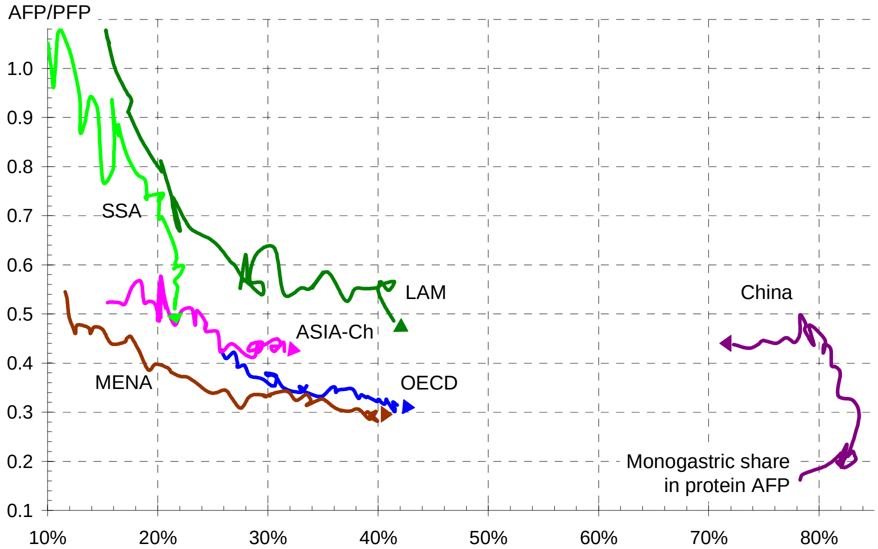

Figure 7. Observed and simulated production of food from livestock (1961-2007)

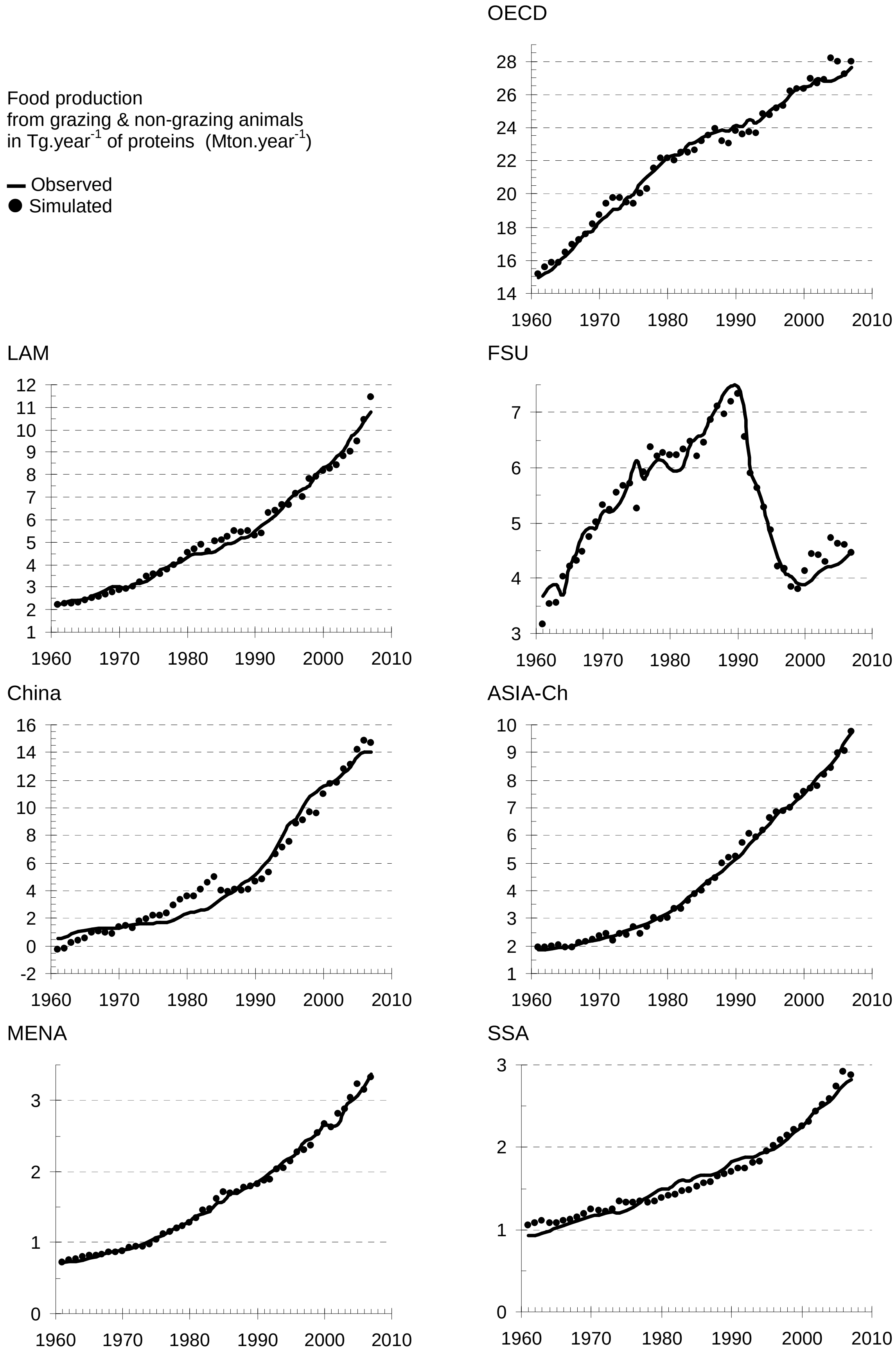

Figure 8. Calories provided by proteins in PFP (1961-2007)

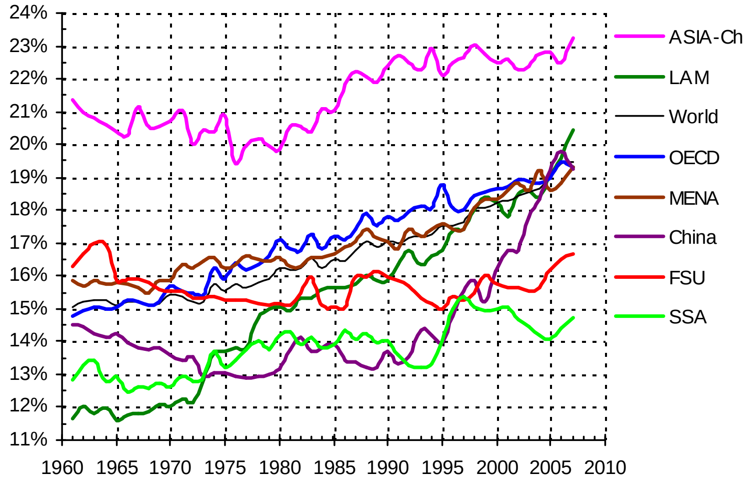

Figure 9. Calories provided by proteins in AFP (1961-2007)

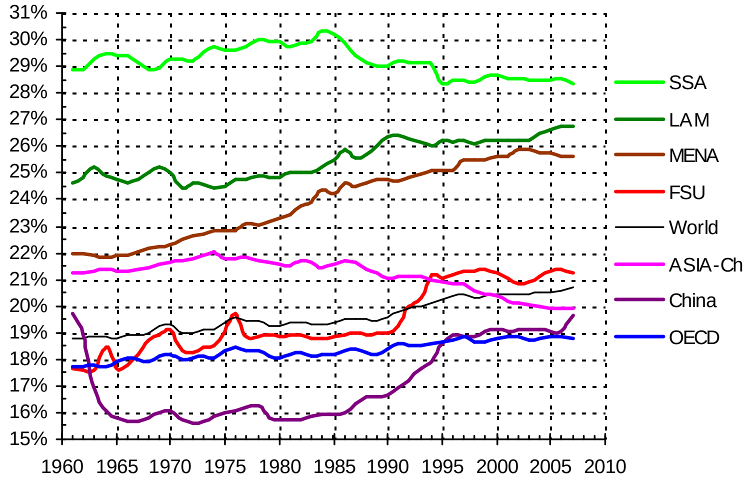

Figure 10. Modelling of Technical Scenarios 1 and 2

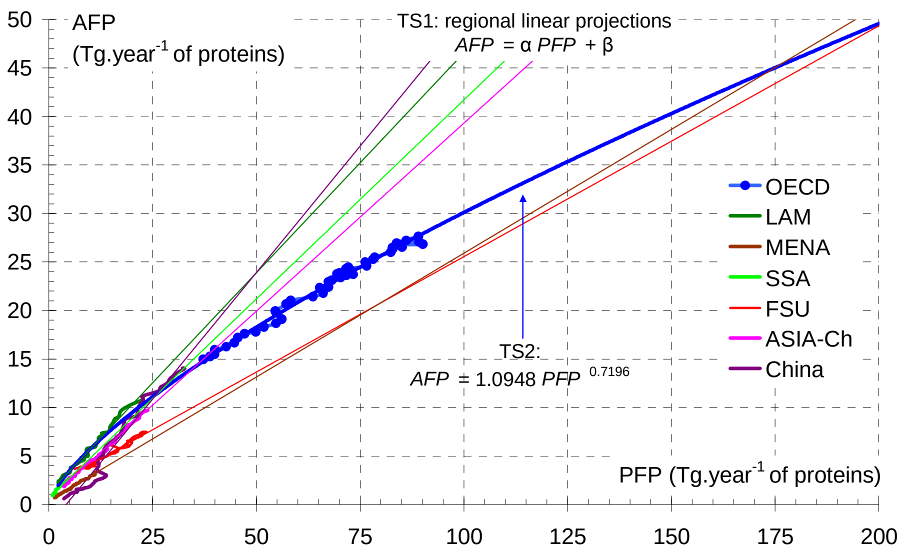

Figure 11. World *PFP* consumptions by usage with TS1 (2050)

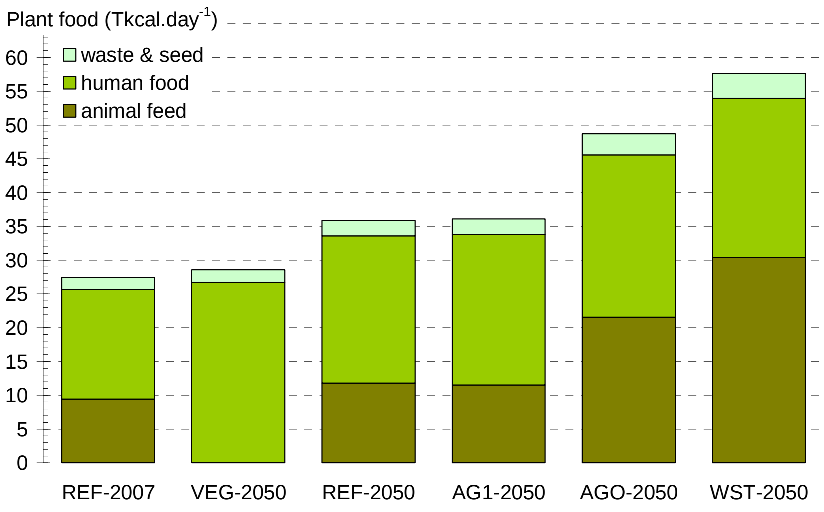

Figure 12. World *PFP* consumptions by region with TS1 (2050)

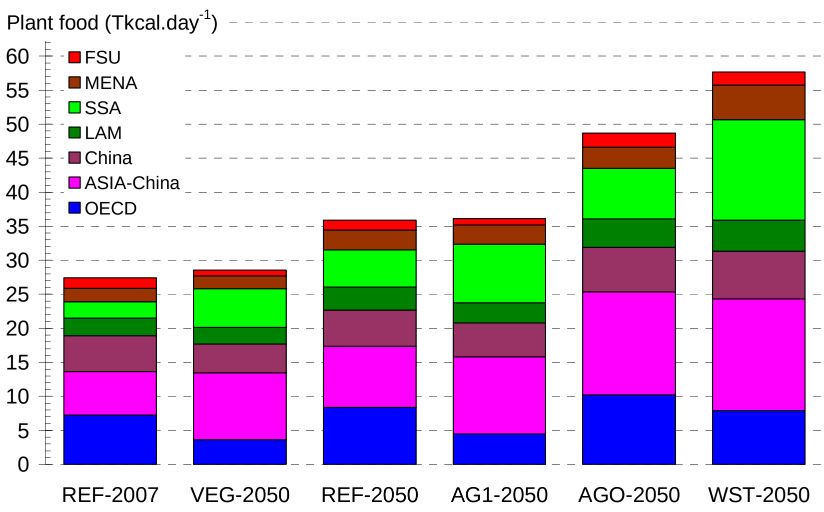

Figure 13. World *PFP* consumptions by region with TS2 (2050)