Chapter 2
Agribiom: A Tool for Scenario-Building and Hybrid Modelling

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Agribiom is a quantitative tool devoted to the analysis of the world's production, trade and use of biomass. Its construction was initiated in early 2006 at CIRAD, with the aim of creating a tool for use in collective scenario-building, such as the Agrimonde project, and in hybrid modelling exercises[1,2].

At this stage, the (past and future) physical balance between food biomass resources and their use is the core issue and driver of Agribiom. Such balances can now be reconstructed (from the 1960s to date) or simulated on various geographical scales (from a country to the whole world) according to certain units and categories designed to:

- provide a tool for retrospective analysis and scenario-building that is sufficiently simple, all-encompassing and robust so that it can attract and mobilise a wide variety of expertise around questions of production, trade and consumption of biomass on national and global scales,
- collect and generate a set of data for developing new analyses and models, especially in fields and on scales in which statistical data and modelling exercises are limited (e.g. conversion of plant biomass into animal biomass on a national scale),
- characterise existing or potential modes of production and consumption of food biomass, and link the specificity of these modes to data, models or debates pertaining to food security, poverty, demand for non-food agricultural products

[1] Especially those undertaken with the CIRED (*Centre international de recherche sur l'environnement et le développement*) in cooperation with the CFE (*Conseil français de l'énergie*) on the subject of "Energy-food competition in land use" (Dorin et al. 2009; Dorin and Gitz 2008).

[2] Hybrid modelling consists in combining economic models with physical and technological data models (ed. note).

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(biofuels, biomaterials, etc.), international trade, exploitation and prices of minerals or other natural resources, greenhouse gas emissions or sinks, conservation of services rendered by ecosystems, and so on.

To fulfil these functions, Agribiom is divided into four work packages, consisting in:

1. collecting, verifying and collating, over several decades, millions of data on national production, trade and uses of agricultural and food products,
2. using these basic data to generate new statistical series that serve for new analyses and new modelling exercises,
3. constructing an interface so that these data and models can easily be shown to various stakeholders (researchers, experts, policy-makers, entrepreneurs, NGOs, etc.), with a view to discussing them and then simulating and debating over various resource-use scenarios for food biomass,
4. interacting with other quantitative tools, especially computable general equilibrium[3] and biophysical models.

This chapter describes the progress made in the first three work packages. Chapter 3 shows some of Agribiom's outputs for a brief retrospective analysis of the world food economy (1961–2003), and in the following chapters, outputs for the Agrimonde scenarios are presented, along with related assumptions and interpretations.

General Organisation of Data Processing

To meet the objectives in terms of retrospective analysis, production of new statistics and models, simulations of new resource-use accounts of food biomass, interaction with various expert knowledge or numerical models, a huge number of historical data are fed into Agribiom (over 30 million non-redundant values in 2008). The treatment of this mass of information is illustrated in Fig. 2.1. SAS® and Microsoft Access® software is used to ensure:

- traceability of operations and calculations thanks to an arrangement of SAS programs between raw data files with variable structures and formats (xls, csv, txt, etc.) and the databases and models developed for the exercise,
- the convergence of these databases and models towards an interface constructed with Access (database management system with SQL code) to view and exploit these databases and models on various possible geographical scales (from a single country to the whole world).

[3] These are macroeconomic models (dealing with a whole economy) that include all activities, production factors and institutions, and therefore all markets (editor's note).

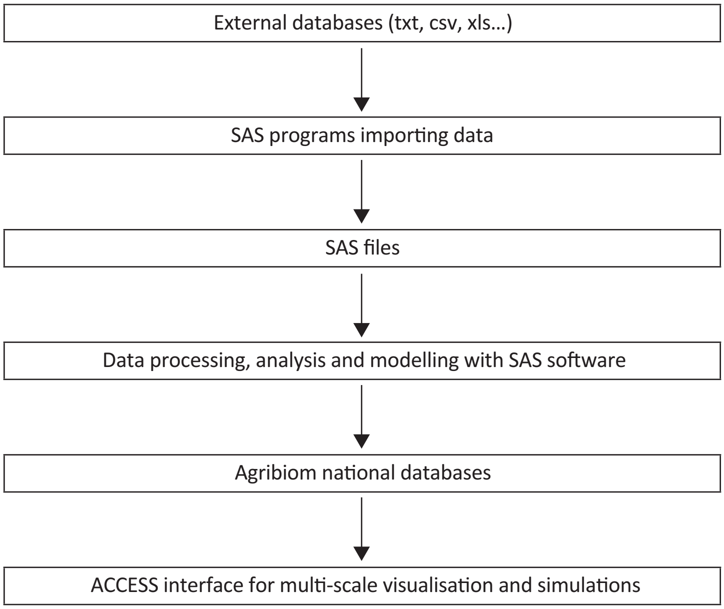


Fig. 2.1 General organisation of data processing

Temporal and Geographical Coverage

The United Nations FAOSTAT service collects, harmonises and disseminates a huge volume of national data on food and agriculture. This large quantity of data can be explained by the FAO's concern to include all agricultural products for human consumption (and not only those traded between countries) as well as all countries (and not only those with enough resources and skills to provide detailed good-quality statistics). Most of our work draws upon these FAOSTAT databases, even though they have certain shortcomings, largely related to the above-mentioned concern for exhaustiveness. These shortcomings can easily be highlighted, as well as the greater reliability of certain other databases focused on particular periods, products or regions. In our work, we favoured a "macroscopic" approach over a "microscopic" approach focused on specific fields, as we were keen, as far as possible, to obtain wide, all-encompassing views of a vast (geographical and historical) landscape rather than a few selective precise photographs of it. This focal distance for observing, analysing and modelling is complementary to others; it affords access to knowledge to which others do not have access, and vice-versa.

Improvements in the reliability and coherence of FAOSTAT data are nevertheless desirable, along with their expansion to areas in which there are no (or no longer) structured series harmonised on an international scale (especially concerning agricultural production factors). In this respect, in June 2006, when the Agrimonde project was launched, the FAO itself embarked on a vast and ambitious reform intended mainly to improve its Supply Utilization Accounts (SUA) and the data comprising them. To do so it excluded data series going back to 1961 ("$FAOSTAT_1$") and, in 2007, proposed new series starting in 1990 ("$FAOSTAT_2$"). Because of this closer historical focus, and for other more technical reasons (reorganisation of product lines and their coding, of the format of basic files, of the content of sections, etc.), we preferred to use the $FAOSTAT_1$ series (FAO 2006). However, the FAO abandoned $FAOSTAT_2$ at the beginning of 2008 and $FAOSTAT_1$ was resumed. This goes to explain why, in 2009, the FAO's SUA and Food Balance Sheets had not been updated beyond 2003. The same applies to most of our series.

Between 1961 and 2003, the earth's surface area did not change—unlike the number of countries and their borders. In the FAOSTAT series, over 250 geographical units have been recorded over the past four decades. We selected 149 units (Appendix 1, p. 241), after excluding a large number of islands and micro-states for which very little or highly irregular data were available, as well as some larger areas with the same lack of reliable statistics: Afghanistan, Antarctica, Bhutan, Iraq, Oman, Papua New Guinea, Western Sahara, and Somalia[4]. In 2000, in comparison with the total (excluding Antarctica) of the FAO for the same year (total named "World+"), this selection represents:

- 98.3 % of human populations (5,983,885 Minhab./6,085,574),
- 98.6 % of cultivated areas (food and non-food crops) (1,512,948 Mha/1,534,945),
- 97.3 % of land areas (13,078,385 Mha/13,443,345).

Our "World" total will therefore be calculated with the entities specified above, the number of which varies from one year to the next: e.g. after 1991, the entity "Soviet Union" was divided up into 15 new units (Russian Federation, Ukraine, etc.). The same applies to the regional totals of a particular zoning of the world. For the Agrimonde scenarios, the zoning used is that of the Millennium Ecosystem Assessment (MA) which groups together countries (or divides up the world) into six regions (Fig. 2.2) (MA 2005b). The distribution of our entities across the six MA regions is detailed in Appendix 1.

This zoning delimits regions considered to be relatively homogeneous according to some indicators. The choice of other indicators could have accounted for their very real internal ecological, socio-economic or historical diversity, with results varying according to the geographical units chosen to carry out the analysis (district, country, etc.). This grouping of areas and change of scale of analysis is necessary, even though it raises various important questions in the estimation of certain values, as in the development and application of models.

[4] The "Belgium-Luxemburg" zone was maintained, whereas from 2000 onwards, the series pertaining to food balances had no data for this set or for either of its units separately (Belgium or Luxemburg). This introduced a slight bias into several evaluations.

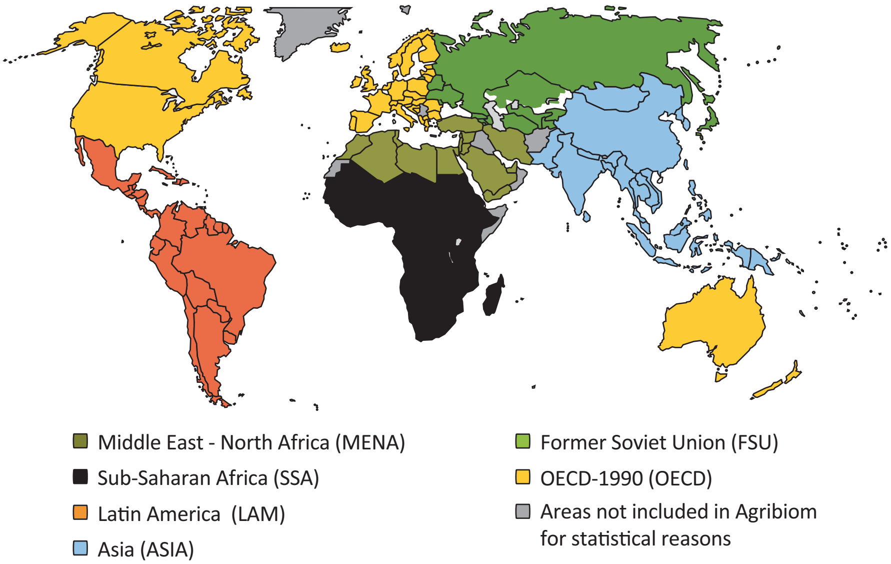


Fig. 2.2 Map of the six regions of the MA. (Source: based on MA (http://www.millenniumassessment.org/documents/document.774.aspx.pdf) Cartographic source: Articque)

Human Populations

Agribiom annual historical country data on human populations are drawn from the FAOSTAT "PopStat" series[5]. This series groups together two sets of estimates by the United Nations Population Division: the "Population-Estimates 2004 rev." and the "Population-Estimates 2006 rev.". The first set was chosen because it describes populations according to their gender (female/male), their dwelling place (rural/urban)[6], their dependence on agriculture ("agricultural population")[7] and their labour force ("economically active population")[8]. The "2006 rev." data set is less

[5] File called "PopSTAT-Annual-Time-Series1" in 2007–2008.

[6] Online FAOSTAT glossary (2008): "Rural population" = "Residual population after subtracting urban population from total population" and "Urban population" = "Usually the urban areas and hence the urban population are defined according to national census definitions which can be roughly divided into three major groups: classification of localities of a certain size as urban; classification of administrative centres of minor civil divisions as urban; and classification of centres of minor civil divisions on a chosen criterion which may include type of local government, number of inhabitants or proportion of population engaged in agriculture, as urban".

[7] Online FAOSTAT glossary (2008): "Agricultural population is defined as all persons depending for their livelihood on agriculture, hunting, fishing and forestry. It comprises all persons economically active in agriculture as well as their non-working dependents. It is not necessary that this referred population exclusively come from rural population".

[8] Online FAOSTAT glossary (2008): "The economically active population refers to the number of all employed and unemployed persons (including those seeking work for the first time). It covers

complete but more up-to-date (2006 for the "2006 rev." data set as opposed to 2005 for the "2004 rev." data set). These two sets give substantially different figures:

- at the beginning of the period (1960s). For 1961, the world population (FAO aggregate "World+") is respectively 3,081 and 2,804 billion,
- at the end of the period (2000s). For 2005, it amounts to 6,465 billion individuals in the first set and to 6,515 in the second.

For projections of human populations in 2050, two data sources per country were mobilised:

- MA projections according to four scenarios (Adapting Mosaic, Global Orchestration, Order from Strength, TechnoGarden), from 2000–2050 in 5-year segments and 21 age groups (0–4 years old, 5–9, etc.) (MA 2005b),
- United Nations projections published on line in 2007 on the UNSTATS website[9], for every year from 2006–2050, based on four hypotheses: a constant fertility scenario, a high variant projection, a low variant projection, and a medium variant projection.

Since our geographical area of study does not include all countries, for reasons outlined in the preceding section, and is not altered in retrospective and prospective analyses to ensure coherent calculations and unbiased comparisons over time, discrepancies are found with our "total world" and the "total world" from other sources, as shown in Table 2.1.

Land Use

Annual historical country data on general land use combine three series of FAOSTAT data:

- [1] the "Land" series as in 2007[10],
- [2] the "Land" series as in 2006[11],
- [3] the "Irrigated area" series as in 2006[12].

The series [1] updates FAO data on land use up to 2005, in which six categories are distinguished:

employers; self-employed workers; salaried employees; wage earners; unpaid workers assisting in a family, farm or business operation; members of producers' cooperatives; and members of the armed forces. The economically active population is also called the labour force".

[9] "Total population (UN Pop. Div. annual estimates and projections) [code 13660]" downloaded on 08/05/2007 at http://unstats.un.org/unsd/cdb/cdb_advanced_data_extract.asp?srID=13660

[10] "RessourceSTAT-Land1.xls" file.

[11] "9541E_0.csv" file.

[12] "9542E_0.csv" file.

Table 2.1 Variations in estimates of world human populations (2000 and 2050)

Year	Source	Total countries (million inhabitants)		Dif.	
		FAOSTAT, UNSTAT, MA	With Agribiom	(Million)	(%)
2000	FAOSTAT—Estimates 2006 Rev.	6,124	5,984	140	2.3
	FAOSTAT—Estimates 2004 Rev.	6,086	5,984	102	1.7
	UNSTAT, 2007—Code 13660	6,086	5,984	102	1.7
2050	MA, 2005—Scenario GO	8,085	7,872	213	2.6
	MA, 2005—Scenario TG	8,812	8,578	234	2.7
	MA, 2005—Scenario AM	9,514	9,265	250	2.6
	MA, 2005—Scenario OS	9,559	9,303	256	2.7
	UNSTAT, 2007—Low variant projection	7,667	7,440	227	3.0
	UNSTAT, 2007—Medium variant projection	9,060	8,800	260	2.9
	UNSTAT, 2007—High variant projection	10,627	10,330	297	2.8
	UNSTAT, 2007—Constant fertility scenario	11,634	11,245	389	3.3

Scenarios: *GO* Global Orchestration; *TG* TechnoGarden; *AM* Adaptating Mosaic; *OS* Order from Strength

- annual crops (called "Arable land")[13],
- plantations ("Permanent crops")[14],
- pastures ("Permanent meadows and pastures")[15],
- forests ("Forests and woodland")[16],
- other emerged land ("Other land"),
- lakes, rivers and other immersed land ("Inland water").

[13] Online FAOSTAT glossary (2008): "Arable land is the land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category. Data for 'Arable land' are not meant to indicate the amount of land that is potentially cultivable".

[14] Online FAOSTAT glossary (2008): "Permanent crops are sown or planted once, and then occupy the land for some years and need not be replanted after each annual harvest, such as cocoa, coffee and rubber. This category includes flowering shrubs, fruit trees, nut trees and vines, but excludes trees grown for wood or timber".

[15] Online FAOSTAT glossary (2008): "Permanent meadows and pastures is the land used permanently (five years or more) to grow herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land). The dividing line between this category and the category 'Forests and woodland' is rather indefinite, especially in the case of shrubs, savannah, etc., which may have been reported under either of these two categories".

[16] Online FAOSTAT glossary (2008) for "Forests and Woodland": "Land under natural or planted stands of trees, whether productive or not. This category includes land from which forests have been cleared but that will be reforested in the foreseeable future, but it excludes woodland or forest used only for recreation purposes. The question of shrub land, savannah, etc. raises the same problem as in the category 'Permanent meadows and pastures'".

Table 2.2 Variations in estimates of the earth's land use (2003)

Surface areas		Total countries (1000 ha)		Dif.	
		FAOSTAT (world+)	With Agribiom	(ha)	(%)
(1) Crops and plantations	Total	1,551,518	1,529,043	22,475	1.4
	annual crops (arable land)	1,413,002	1,392,951	20,052	1.4
	plantations (permanent crops)	138,516	136,093	2,423	1.7
	irrigated area (total area equipped for irrigation)	276,500	270,273	6,227	2.3
(2) Pastures (permanent meadows and pastures)		3,415,704	3,325,988	89,716	2.6
(3) Forests (forest)		3,966,660	3,904,776	61,883	1.6
(4) Other emerged land (other land)		4,078,908	3,891,722	187,186	4.6
(5) Lakes, rivers & other (inland water)		429,780	426,910	2,870	0.7
Total (1)+(2)+(3)+(4)		13,012,789	12,651,530	361,260	2.8
Total emerged area (land area)		13,013,621	12,651,530	362,091	2.8
Total (1)+(2)+(3)+(4)+(5)		13,442,569	13,078,440	364,130	4.6
Total area (country area)		13,443,401	13,078,440	364,961	2.7

The total of these areas should theoretically be equal to the "total area of the country" (Table 2.2), a total which the FAO provided with other intermediate aggregates such as "Arable and Permanent Crops" (which we called "cultivated area"), "Agricultural Area" (cultivated area + pastures), etc.

With the publication of the series [1], FAOSTAT adds new and important sections (e.g. "Fallow land", "Temporary meadows & pastures"). However these were seldom provided, or were insufficiently updated until 2005 for irrigated areas, which were imported from the former series [3] covering the period 1961–2003. The series [1] also proposes new estimates for forests, without going back further than 1990. Before then, data from the series [2] were imported, and the "Other land" category was adjusted so that the sum of the six land use categories did not exceed the total surface area of the country. Finally, this series [1] does not correct certain shortcomings, errors and inconsistencies on land use noted in previous years in this series[17]: certain corrections had to be made in order to smooth some series.

In Agribiom, annual and permanent croplands are merged into a single category, "cultivated land". For the simulations, the following are distinguished within this category: the "food cultivated area" (FCA) and the potentially large "non-food cultivated area" (NFCA: rubber, tobacco, fibres, eucalyptus, etc.). Until the 2000s, these NFCA were considered as nil even though this was not the case[18], mainly for the following reason: we had decided not to use the "harvested areas" per crop as provided in the FAO series "prodSTAT", because our attempts to relate these data

[17] The surface area of Spain decreased then increased between 1990 and 2003; the surface area of Greenland increased by 6.9 million hectares between 1996 and 1997, etc.

[18] FAO figures indicate that in 2003, on the global scale ("Word+"), the (gross) harvested areas in fibres, rubber and tobacco totalled slightly over 46 million hectares, which represents 3% of the (net) cultivated area (1,552 Mha).

to the net cultivated land of series [1] too often led us to surprising or inconsistent results.

Finally, annual national data on coasts and maritime areas (dated from 1990–2000 depending on the case) were imported from a database developed by the University of Hamburg. This database, temporarily available on the university's website (www.fnu.zmaw.de), compiled data of various origins (World Resources Institute, CIA World Fact Book, Delft Hydraulics, Gallup and Sachs, etc.) including The Global Maritime Boundaries Database (GMBD) for continental shelves.

Potentially Cultivable Lands

At the end of the 1990s, the aim of the FAO and the International Institute for Applied System Analysis (IIASA), via Fischer et al. (2001, 2000, 2002), was to carry out a new evaluation of the world's potential agricultural production by means of recent breakthroughs in satellite imagery and GIS (Geographical Information System) techniques. This approach, called Global Agro-Ecological Zones (GAEZ), is based on the Agro-Ecological Zones (AEZ) which has been the subject of various studies over the past 20 years. The aim of the AEZ is to identify and characterise climatic zones, soils and lands suitable or not for agriculture.

The GAEZ method consists roughly in adjusting and combining data at a geographical scale which is far finer than the national one, i.e. grid-cells of a few square kilometres. These data belong to the following two sets: data on agro-ecological environments, on the one hand, and data on possible land utilisation, on the other.

Data on Agro-Ecological Environments

These data concern:

- the climate (CRU data/model at 30 min[19] latitude/longitude, with 1961–1990 mean values for the so-called "reference" climate, and IPCC [Intergovernmental Panel on Climate Change] data for the climate scenarios),
- the type of soil (FAO/UNESCO DSMW database on 2.2 million cells of 5 min latitude/longitude),
- the slopes (digital elevation model GTOPO30 at 30 arc-second latitude/longitude),
- the "current" land occupation (12 "aggregate" types of occupation drawn from GLCC maps at 30 arc-seconds latitude/longitude, based on satellite images probably taken in 1992/1993).

[19] 1 degree (60 min) at the equator is equivalent to about 111 km; 30 arc-seconds = 1 minute = 1,854 km at the equator.

Data on Possible Land Utilisation

462 land utilisation types (LUT)[20] were characterised in GAEZ by combining:

- 154 agricultural products including some fodder and pastures, or rather 27 species broken down into various crop-types attached to a climate zone: 8 cereals (83 crop-types: 4 for hibernating wheat, 12 for non-hibernating wheat, 13 for grain maize, 6 for silage, etc.), 3 tubers (8 crop-types: 4 potatoes, 1 manioc, 3 sweet-potatoes), 3 peas and lentils (17 crop-types), 6 oilseeds (25 crop-types, of which 1 palm and 1 olive), 1 fibre (7 crop-types for cotton), 2 sugar crops (6 crop-types: 1 sugar cane and 5 sugar beet), 1 fruit (banana/plantain) and 3 fodder (5 crop-types: 1 alfalfa, 4 pastures of forage grass, 4 pastures of leguminous fodder plants),
- 3 levels of input and management, successively labelled "low" (no use of chemical fertilisers, pesticides or improved seed), "intermediate" (use of certain "modern" inputs and partial mechanisation) and "high" (similar to commercial farming as practised in Western Europe and North America).

The combination of these data in each grid-cell led the GAEZ team first to calculate potential yields (of biomass and of product harvested) without any constraint other than temperature and solar radiation, and then to revise these yields successively in relation to:

- "agro-climatic constraints" (rainfall, mainly),
- "soil and terrain constraints", including, in particular, slopes (which restrict the intensification of production via mechanisation, irrigation, etc.) and the need to leave land fallow (to ensure long-term fertility of soil in the area under consideration).

These constraints were used by the team to estimate yields in the case of rainfed and irrigated crops (without assuming real availability of water nor the quality thereof), and according to the three levels of inputs and management mentioned above (low, intermediate and high).

The final outputs are estimates of surface areas (1,000 ha), by crop (wheat, rice, etc. with some aggregated categories, including "cereal crops" and "all crops"), by input level (low, intermediate and high) and by the use or otherwise of irrigation (at least for the high and intermediate input levels), for four "suitability classes" for agriculture: VS (very suitable), S (suitable), MS (moderately suitable) and mS

[20] The crop catalogue database provides a quantified description of LUT. Factors included are crop characteristics such as: duration of crop growth cycle, duration of individual crop development stages, photosynthetic pathway, crop adaptability group, maximum leaf area index, harvest index, development stage-specific, crop water requirement coefficients, yield reduction factors relating to moisture stress and yield loss, food content coefficients (energy, protein), extraction/conversion rates, crop by-product/residue coefficients, and commodity aggregation weights. Also included are parameters describing, for both rain-fed and irrigated LUT, thermal requirements, growing period requirements, and soil and terrain requirements, applicable in tropical, subtropical, temperate, and boreal environments, respectively.

(marginally suitable), along with NS (not suitable land) and NAG (land for settlement and infrastructure). The exercise also led to the estimation of maximum potential yields for each of the combinations listed above.

All the GAEZ data expressed per country and available on line (FAO and IIASA 2000) were imported, and those used for the Agrimonde project (after aggregation per MA region) are presented in Fig. A2.4. The examination of these data reveals certain difficulties:

- interpretation of "All crops" and "Mixed inputs" aggregates is difficult due to fuzzy definitions,
- the areas presented in the three sources (FAO and IIASA 2000; Fischer et al. 2000, 2002) are not identical[21],
- GAEZ country areas are much the same as those of the FAO (see "Land use", p. 30) however there are exceptions[22] which cannot be explained by immersed land areas,
- the year of evaluation for surface areas of forests and lands for settlement and infrastructure (housing, roads, etc.) is not provided (probably 1992/1993),
- GAEZ potentials are not expressed by category of current land use, except for forests. However total forest surface areas are very different (generally far inferior) to those of FAOSTAT and, more generally, to other sources of data on land use during the 1990s,
- similar estimates of potential croplands were made after simulation of different scenarios of (uniform) global warming (+1 °C, +2 °C, etc.), but these data have proved to be inaccessible.

Food Biomass Resource-Use Balances

As announced in the introduction to this chapter, the core subject of Agribiom is the balance—either reconstituted for the past or simulated for the future—between food biomass resources and their use, with three particularities.

The first particularity is that our resource-use balances are calculated for the near totality of "food biomass" that is divided into five "compartments" based on the origin of the products and on land use:

- vegetal/plant products (vege),
- animal products, divided into products of grazing animals comprising ruminants and large herbivorous animals (rumi), and products of non-grazing or monogastric animals (mono),

[21] Example: for the VS + S + MS potential in rainy conditions with a mixed level of inputs, we find successively, for North America, 384.2 Mha in online data, 405.5 Mha in the 2000 report, and 366.3 Mha in the 2002 report.

[22] Bhutan (14 % difference), Suriname, Liberia, Morocco, Ecuador, Belgium-Luxembourg, Saudi Arabia, United Arab Emirates, Libya, Netherlands, Kuwait, India, Rwanda, Niger, Guinea-Bissau, Tunisia (6 %), etc.

- aquatic products (plant or animal), divided into freshwater products (aqua) and marine products (mari).

By "food biomass" we mean any organic matter that, in its primary form, can either serve as food for human consumption—and that does effectively serve that purpose in a form that is processed to a greater or lesser degree (grain, oil, bread, cornflakes, etc.)—, or else that is entirely (e.g. grains of maize) or partially (e.g. oilcakes) used for animal consumption or other purposes (seed, ethanol or biodiesel, green chemistry, etc.). This definition therefore encompasses a wide range of agricultural products but not such products as rubber, plant fibres, silk, wool, leather, essential oils, fodder (alfalfa, silage, straw, bagasse, etc.), and so on[23].

The second particularity of our resource-use balances is that we use food calories (kcal) as a common unit of volume for consumption, production and trade of biomass. All food biomass provides energy for humans. This amount of energy, per gram or kilogram of product ingested, is particularly high with plant or animal oils and fats, and particularly low with fresh produce such as citrus fruit, tomatoes, shellfish, and tropical products such as tea, coffee or pineapples. This unit is used to obtain the sum of (and group into "compartments") quantities of products that cannot feasibly be added up when they are expressed in tons, litres or other units. Yet, even though the analysis of food calories has several advantages, it also has limitations, especially from two points of view: economic (the value of a calorie of a grain of maize is not equivalent to that of a grain of coffee) and nutritional (Deaton and Dreze 2009; Dorin 1999). In this respect, it is important to highlight here that a satisfactory diet as regards calorie content does not necessarily have the required micronutrients (vitamins and minerals, particularly present in fruit and vegetables) nor even macronutrients (carbohydrates, proteins and lipids), the diverse forms of which have to be consumed in the right quantities (neither too much nor too little) if a person is to live a healthy and active life. In view of these and other considerations, we tried to express our caloric balances as far as possible according to their carbohydrate, protein and lipid content, on the basis of an average content of, respectively, 4, 4 and 9 kcal per gram.

The third particularity is that the annual resources and uses of food biomass are represented and then simulated according to the structure of the equation presented below:

$$\begin{aligned}&(\mathrm{area}_{r,i}\,\mathrm{x}(\mathrm{prod}_{r,i}/\mathrm{area}_{r,i})) - \mathrm{trad}_{r,i} + \Delta\mathrm{stoc}_{r,i} = \\ &(\mathrm{popu}_{r}\,\mathrm{x}(\mathit{food}_{r,i}/\mathrm{popu}_{r})) + \mathrm{feed}_{r,i} + \mathrm{seed}_{r,i} + \mathrm{vana}_{r,i} + \mathrm{wast}_{r,i}\end{aligned}$$

where:

i is a compartment of food biomass (vege, rumi, mono, aqua, mari)

[23] Our resource-use balances do not include live animals (although their trade and stock variations, in particular, do have an impact on food balances). One of the reasons is that only their products (milk, meat, etc.) are taken into account in the SUA of the FAO.

r is a region of the world (country or group of countries: MENA, SSA, LAM, ASIA, FSU, OECD)

$\text{area}_{r,i}$ is an area (ha) in a region r: the food cultivated area when i = vege, the inland water area when i = aqua, the continental shelf area when i = mari; otherwise (i = rumi, mono): area = 1

$\text{prod}_{r,i}$ is the production of foodstuffs i in a region r (kcal)

$\text{prod}_{r,i}/\text{area}_{r,i}$ is the yield of foodstuffs i (kcal/ha) in a region r when i = (vege, aqua, mari); otherwise (i = rumi, mono), $\text{prod}_{r,i}/\text{area}_{r,i} = \text{prod}_{r,i}$

$\text{trad}_{r,i}$ is the net trade balance (total exports—total imports) of foodstuffs i (kcal) in a region r

$\Delta\text{stoc}_{r,i}$ is the stock variation of foodstuffs i (kcal) in a region r (negative sign if destocking)

popu_r is the human population (inhabitants) in a region r

$\text{food}_{r,i}$ is the quantity of foodstuffs i (kcal) used in a region r for feeding the human population, including wastage occurring in the household

$\text{food}_{r,i}/\text{popu}_r$ is the average food consumption (including wastage) per person (kcal/capita) of foodstuffs i in a region r

$\text{feed}_{r,i}$ is the quantity of foodstuffs i (kcal) used in a region r for feeding animals

$\text{seed}_{r,i}$ is the quantity of foodstuffs i (kcal) used in a region r for reproductive purposes (seed, eggs for hatching, etc.)

$\text{vana}_{r,i}$ is the quantity of foodstuffs i (kcal) used in a region r for non-food purposes: lubricants, energy, cosmetic, biomaterial, etc.

$\text{wast}_{r,i}$ is the wasted quantity of foodstuffs i (kcal) in a region r between the general available quantities (Production—Exports + Imports +/- Stocks) and their allocation to a specific use (food, feed, etc.); this does not include losses occurring before and during harvesting, and wastage occurring in the household.

In agribiom, this equation must be verified:

- at the level of each biomass compartment i (e.g. vege, rumi),
- on the scale of each region r considered (e.g. MA regions),
- in such a way that the sum of the net trade balances (trad*:* exports-imports) per compartment i is nil on a global scale.

The volumes of biomass are expressed in terms of food calories, which may be total calories but also calories only from carbohydrates, proteins or lipids.

The first term of the equation represents the resources: regional biomass production plus or minus the net trade balance and net stock variations. For plant and aquatic biomass, regional production is represented as a function of the production area (ha) and its (partial) productivity in food (kcal/ha)[24]. As this representation is not possible for terrestrial animal biomass (rumi and mono)[25], other formulations had to be used for the simulation of such production (see "Animal production models", p. 42).

[24] This representation of production is very simple but raises certain questions (area and yield) rather than others (for instance, it does not allow the analysis of the size of the farming population and its—partial—labour productivity).

[25] The production of this biomass cannot easily be linked to specific numbers of hectares.

The second term of the equation represents regional biomass uses, of which the human food consumption is represented as human populations (number of people) who consume varying quantities of food biomass per person (kcal/capita).

This representation of resources and uses of food biomass is closely related to the statistical series that could reasonably provide historical data, on the scale of each country in the world, and over a relatively long period. The series mobilised for human populations (popu) and areas (area) are presented above (see "Human populations" and "Land use" page 30). The others are derived from a far larger database which contains and compacts detailed data series on the production and trade of agricultural products: the Commodity Balances of the Supply Utilization Accounts (SUA) compiled by the FAO (FAO 2006). The SUA have the major advantage of being developed: 1) for almost all countries in the world; 2) for more than 40 years (1961–2003); 3) for over 120 product lines; 4) and so that, for each of these lines, the evaluation of national "availabilities" (production + imports—exports—stock variations) shows a balance with the evaluation of national "use". These uses are broken down into six sections: the five mentioned above (food[26], feed[27], seed[28], vana[29], wast[30]) and a sixth called "food manufacture" (cf. infra).

[26] Online FAOSTAT glossary (2008): food "Data refer to the total amount of the commodity available as human food during the reference period. Data include the commodity in question, as well as any commodity derived therefrom as a result of further processing. Food from maize, for example, comprises the amount of maize, maize meal and any other derived products available for human consumption. Food from milk relates to the amounts of milk as such, as well as the fresh milk equivalent of dairy products".

[27] Online FAOSTAT glossary (2008): feed "Data refer to the quantity of the commodity in question available for feeding the livestock and poultry during the reference period, whether domestically produced or imported".

[28] Online FAOSTAT glossary (2008): seed "Data include the amounts of the commodity in question set aside for sowing or planting (or generally for reproduction purposes, e.g. sugar cane planted, potatoes for seed, eggs for hatching and fish for bait, whether domestically produced or imported) during the reference period. Account is taken of double or successive sowing or planting whenever it occurs. The data of seed include also, when it is the case, the quantities necessary for sowing or planting the area relating to crops harvested green for fodder or for food (e.g. green peas, green beans, maize for forage). Data for seed element are stored in tonnes (t). Whenever official data were not available, seed figures have been estimated either as a percentage of supply (e.g. eggs for hatching) or by multiplying a seed rate with the area under the crop of the subsequent year".

[29] Online FAOSTAT glossary (2008): vana "Data refer to quantities of commodities used for non-food purposes, e.g. oil for soap. In order not to distort the picture of the national food pattern quantities of the commodity in question consumed mainly by tourists are included here (see also "Per capita supply"). In addition, this variable covers pet food".

[30] Online FAOSTAT glossary (2008): wast "Amount of the commodity in question lost through wastage (waste) during the year at all stages between the level at which production is recorded and the household, i.e. storage and transportation. Losses occurring before and during harvest are excluded. Waste from both edible and inedible parts of the commodity occurring in the household is also excluded. Quantities lost during the transformation of primary commodities into processed products are taken into account in the assessment of respective extraction/conversion rates. Distribution wastes tend to be considerable in countries with hot humid climate, difficult transportation and inadequate storage or processing facilities. This applies to the more perishable foodstuffs, and especially to those which have to be transported or stored for a long time in a tropical climate.

These annual country accounts are in tonnes. For the 109 lines of what we consider as "food biomass" (Appendix 1, p. 241), these tonnages have been converted into total calories and into calories derived from macronutrients (carbohydrates, proteins, lipids), based on FAO references (2003), sometimes USDA references (2006), and on the equation $Kcal_{total} = (4 \times g_{carbohydrates}) + (4 \times g_{proteins}) + (9 \times g_{lipids})$. In the particular case of feed (e.g. soybean oilcakes), calorie and macro-nutritional equivalents have been subtracted from the calorie and macro-nutritional values of the primary product (e.g. soybean), from the calorie and macro-nutritional values of a secondary product (e.g. soybean oil), and from a world average extraction rate of that product calculated with the FAO's SUA tonnages for the entire period under consideration (e.g. 18 % for soybean oil). Once these conversions into calories had been performed, the lines were aggregated into compartments, as shown in Appendix 1, with few specific cases subject to questionable allocation[31].

The SUA offers a unique data source for assessing and analysing general trends in production, trade and use of biomass. However this accounting is imperfect and complex. In particular, we had to formulate and test various options for classifying lines into "primary" or "secondary" products, in order to avoid double counts (especially for production) and finally to obtain relatively balanced resource-use ratios on a global scale, in terms of total calories as well as macronutrients, over 43 years, without the "food manufacture" section. This section relates to volumes of "primary" products (e.g. groundnuts, produced locally and/or imported), used for local production of one or several "secondary" products appearing in the SUA (e.g. groundnut oil and groundnut oilcakes) according to processing yields for which data are not available. These difficulties are compounded by the fact that some products such as alcohols are derived not from a single primary product but from several products (cereals, grapes, sugars), which may themselves be "secondary" products (sugars in particular, from sugar beet or sugar cane). After multiple tests on all the countries for the whole period 1961–2003, we treated, for example, sugars and molasses as primary products, and consequently excluded from the analysis the volumes of sugar cane and sugar beet from which they were obtained[32].

Furthermore, a perfect resource-use balance is not obtained because the export volumes do not match the import volumes. These problems, among others, triggered a FAOSTAT reform in 2006, which was subsequently abandoned in 2008. With the calorie balances calculated here, we find that in the vast majority of cases the total use is less than total resources. This discrepancy can be explained in various possible ways[33] and is significant in several countries, especially the US where about

Waste is often estimated as a fixed percentage of availability, the latter being defined as production plus imports plus stock withdrawals".

[31] For instance, the line "Animal fats (raw)" was allocated to rumi even though this line is most probably also an output of mono and mari products.

[32] This biomass is not traded much internationally, therefore no bias is introduced at this level. However it may, as in China, be used as feed and not only for producing sugar.

[33] We note the absence of SUA data for Belgium and Luxembourg (referenced in our base) from the year 2000 onwards, although this region is a net importer of plant calories (about 50 Gkcal/day since 1975); complete absence of SUA data for countries excluded from our base for this reason

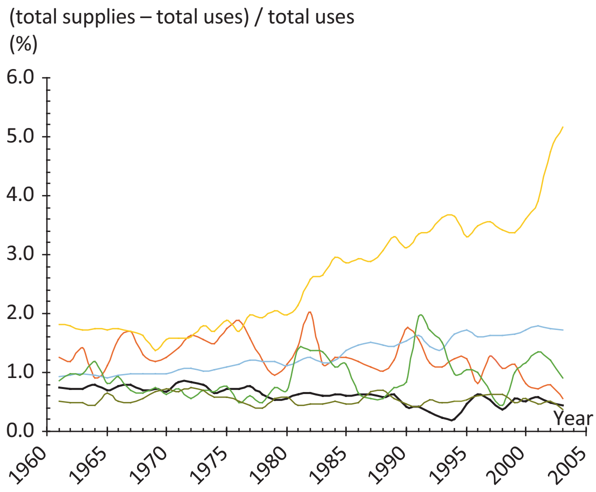


Fig. 2.3 Difference between supplies and uses of plant food calories (1961–2003)

10 % of plant food resources "disappeared" in this way in the early 2000s. But for the vast majority of countries, these gaps are far smaller: less than 3 % (US included) in the early 2000s on the world scale, and less than 2 % over 43 years for five of the six MA regions (Fig. 2.3). With stock variations, these gaps represent what we call "Residue" in the simulations.

Non-Food Biomass

The term "biomass" denotes a wide range of matter corresponding to differing conceptions and definitions, from organisms living underground or underwater, to the leaves of trees and birds in the sky, from organic matter in the process of formation to that which is fossilised in the form of oil, natural gas, coal, lignin or peat. Here, by "non-food biomass", we mean:

- the organic "by-products" or "residues" from harvests of "food biomass": straw, stalks and cobs, wool, leather,
- agricultural products (including from livestock farming and fishing) that cannot be consumed by humans in their primary form: rubber, cotton or other fibres, silk, alfalfa and other fodder, grass,
- the organic "by-products" or "residues" from harvests mentioned above,
- wood in various forms (trees, fuel wood, etc.).

(e.g. Iraq, Afghanistan, Somalia) whereas they are probably net importers of substantial quantities of food; under-estimation of certain uses (including waste); overestimation of production or exports; incorrect assumptions in our treatment of the section "Food manufacture"; etc.

Various series of FAO national data (SUA and other) make it possible to evaluate the tonnage of numerous types of non-food biomass listed above, along with the evolution of these volumes over recent decades, either directly (tobacco, rubber, fibres, wool, leather, fuel wood, industrial wood, etc.) or indirectly (crop residues, standing forest biomass, etc.). Even though compilation and processing of these data within Agribiom need to be continued, our simulation tool makes it possible to investigate the question of competition/complementarity between food and non-food biomass through:

- land use, with varying surfaces of forests, pastures and "non-food cultivated areas" (nfca),
- non-food uses of food products (vana),
- models of animal production using, among other things, quantities of food products used as feed (see feed and models below).

Animal Production Models

This section first shows the importance and the difficulty, in a resource-use approach like Agribiom, of estimating the links between animal productions and plant resources available for these productions. It then proposes a first system of estimation that can serve to capture significant differences between technologies existing in this field at the world level.

Problematic Data and Representations

Animal husbandry—here, of land animals only—provides food for human beings (milk and dairy products, meat, eggs, etc.), of which people tend to eat more when their income rises. Along with the growth of human populations, the demand for animal products is expected to increase steadily in the future. Animal husbandry also provides many other services, for instance for savings, transport and traction, fertilisation of the land (animal manure), cooking (dried dung), lighting, washing or cosmetics (tallow and other animal fats), clothing (wool, leather, feathers, down, etc.), the recycling of organic waste, the maintenance of landscapes and areas rich in carbon and biodiversity, etc. Animals also fulfil religious or social functions (e.g. pets). They directly and indirectly employ a large number of people, and use just over 80 % of so-called "agricultural" land, with 3.3 billion hectares of pastures[34] and over half a billion hectares of cultivated land[35]. Animal husbandry is also cause for

[34] See definition of "land use" p. 30 and Chap. 3, p. 58.

[35] According to our estimations based on FAO data, in 2000, about one third of plant calories consumed in the world were used for animal feed, with major variations in this rate from one region to another (see Chap. 3, p. 63).

concern when it comes to sanitary problems (epizootics) and environmental issues, especially regarding soil (erosion due to overgrazing), water (consumption, pollution) and greenhouse gas emissions (Steinfeld et al. 2006).

Yet, despite the importance of animal husbandry from an economic or ecological point of view, there is a serious lack of statistical data on the subject on a global scale. Animal products other than food are often poorly evaluated (and sometimes not at all), as are production factors other than "concentrates" (cereals and oilcakes): labour, capital, inputs such as veterinary products, etc. From the point of view of animal feed for instance, this is particularly problematic when representing the process of conversion of plant biomass into various kinds of animal biomass, for the purpose of global foresight related to land use. In particular, in the case of large herbivorous animals and ruminants, biomass other than concentrates can be (and is in fact) provided as a supplement or substitute: annual fodder[36], grasses (green or dried) and other types of biomass from meadows, pastures, savannah and various other areas (including forests), crop residues (straw, stalks, haulm, etc.), food residues (peels and other discarded parts), etc. Some authors have attempted to quantify these different animal food resources on national or continental scales, for example Devendra and Sevilla (2002), Wirsenius (2003), Bouwman et al. (2005) and Smeets et al. (2007). Along with quantities, the evaluation of the quality of this biomass is equally important but also poorly known (dry matter, digestibility, energy, proteins, etc.). Finally, for all these sources of feed, much like the others (concentrates), there is a third significant lack of statistics at national scales: the distribution of animal consumption of biomass per species (horses, cattle, sheep, pigs, poultry, etc.) and/or by animal product (milk, meat, etc.).

Agricultural and food foresight exercises however use rates of conversion A (a_{11}, ..., a_{nk}) of a particular biomass i (i_1, ..., i_n) into an animal product P (p_1, ..., p_k). The biomass i is generally limited to volumes of concentrates (cereals, oilcakes), and the products P to volumes of milk (cow, buffalo, goat, etc.), meat (beef, pork, etc.) and eggs, or to a type of animal (calf, cow, bull, etc.). Rates A depend on the units of volume used for i, which may be kilograms of dry matter (Bouwman et al. 2005, Delgado et al. 1999), kilograms of protein (Sebillote 2001), kilocalories (Collomb 1999; Griffon 2006; Malassis and Padilla 1986), etc. These rates A are evaluated in two main ways referred to as the "physiological approach" and the "statistical approach".

The "physiological approach" seeks to evaluate rates A in relation to animals' individual physiological needs (for their maintenance, nutrition, growth, lactation, draft power, pregnancy, etc.), to the composition of herds and flocks (breeds, age, sex and weight of animals), and to local characteristics of available biomass i. In concrete terms, this approach requires a large number of assumptions to be made

[36] In the SUA (Commodity Balances) of the FAO (2006), there are 5 lines for fodder: *Alfalfa for forage and silage*, *Clover for forage and silage*, *Maize for forage and silage*, *Rye grass for forage & silage* and *Sorghum for forage and silage*. These lines are rather limited in number compared to numerous other productions of fodder existing around the world. They are also not provided for large countries such as Brazil, China and India. Because of these limitations we chose not to use these FAO data on fodder, despite their importance.

when we work on national scales, for the past and, even more so, for the future. The "statistical approach" consists in evaluating A in relation to volumes i and P observed at a certain point in time in a certain area and, for the future, in maintaining or altering A according to various experts' assumptions, to be made on all future feed sources i (i_1, ..., i_n) and other production factors, as well as on the impact of these assumptions on each A value (a_{11}, ..., a_{nk}).

In both cases (physiological approach and statistical approach), the representations and coefficients used to simulate the future tend, in practice, to move closer to the situations that are better referenced today, such as industrial breeding and experimental stations aimed at improving the productivity of dairy, meat or egg farms. Even though major progress has been made and will continue to be made in industrial forms of production, we cannot outright exclude, in scenario-building exercises, the fact that other forms of livestock farming will still exist, will be improved or will emerge in the future. These may effectively exploit certain local resources, or provide various forms of income and services to agrosystems and populations with little financial and logistic capital, as in most countries of the South today.

In view of all these considerations, we attempted to improve the representation and modelling of animal food productions at global level. Our approach was resolutely statistical and was divided into two main phases:

- the first involved building a database connecting various national data: 1) relative to animal production and to agricultural production factors; 2) with a large number of countries and over a large number of years (1961–2003) in order to obtain a satisfactory sample of measurements reflecting varied technological options/evolutions; 3) using aggregates and units liable to reveal general and robust phenomena (vege, rumi, mono, aqua and mari compartments quantified in terms of food calories, proteins or lipids),
- the second involved searching, in this database—that we would have preferred to be more complete (on annual fodder consumption, crop residues, pasture quality, etc.)—, for the statistical relations between animal food production and variables liable to explain this production. This research was geared towards the elaboration of "animal production functions".

Following the first stage, it was shown, in particular, that the partial productivity of plant feed (cereals and oilcakes, mostly) was effectively highly variable in space and time, in terms of total calories (Fig. 2.4) or proteins (Fig. 2.5). Long-term simulations of animal production, with a fixed coefficient for this production factor only (cereals and oilcakes, mostly), therefore present limits that the second stage (animal production functions) aims to transcend.

Regional Animal Production Functions

In microeconomics, a production function expresses the relationship between the inputs used by a firm and its production. It indicates, in the form of an equation or graph, what the firm can produce, based on various quantities and combinations of

Fig. 2.4 Plant food calories used to produce one calorie of animal foodstuff (1961–2003)

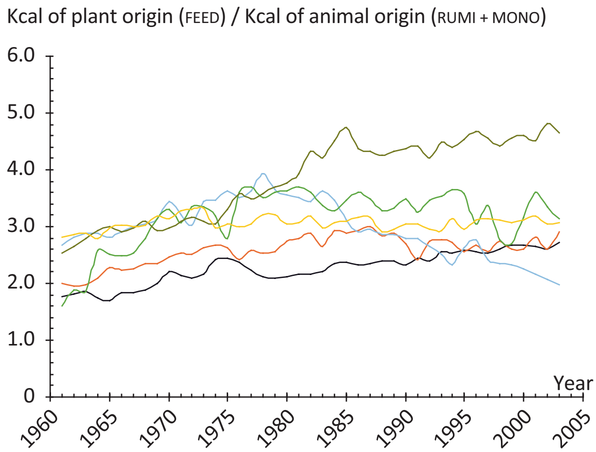
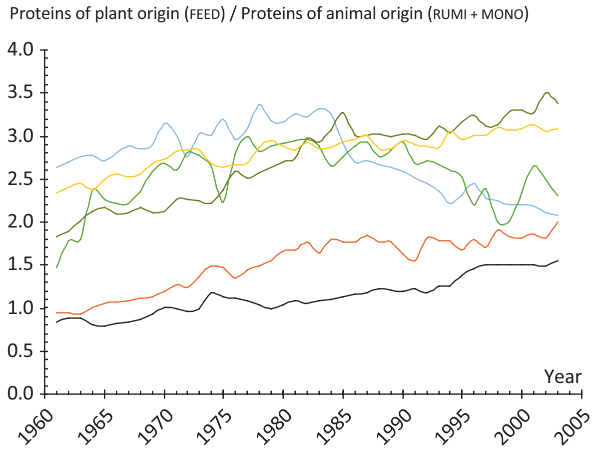


Fig. 2.5 Plant food proteins used to produce one protein of animal foodstuff (1961–2003)



production factors. In general, the production function can be written $Q=f(x_1, \ldots, x_n)$ where Q is the quantity of an output, and $x_1, \ldots, x_n$ are quantities of production factors (labour, capital, inputs, etc.). This function can take different forms (linear, quadratic, Cobb-Douglas, CES, etc.), depending on the technology (whether marginal returns are decreasing or not, whether there are economies of scale or not, whether production factors are highly substitutable or not, etc.). This form is selected depending on the data and the aspects of the technology examined.

In our work, we sought to establish production functions:

- on the scale not of a firm but of a country (or of several countries grouped together in a region), which is often referred to as "cross-country production functions",
- using panel data over a 43-year period (1961–2003),
- in order to estimate annual productions of animal foodstuffs (milk, meat, eggs, etc.) converted into calories or protein equivalents (Gkcal) and grouped together

in two categories only: foodstuffs from “ruminants and large herbivorous animals” (rumi) and foodstuffs from “monogastric animals” (mono),
- with available data on some production factors used—entirely or partially—for these animal productions: feed of plant or animal origin (Gkcal of total calories or calories provided by proteins only), pasture area (thousands of hectares), human labour (thousands of farm workers), tractors (units), etc.

In other words, we sought to design multi-product production functions whose general form is $F(X, Y)=0$, where $X=(x_1, ..., x_n)$ is the vector of production factors and $Y=(y_1, ..., y_m)$ the vector of outputs produced with these factors. This type of function makes it possible, in particular, to distinguish the productivity of the feed in terms of products of rumi on the one hand and products of mono on the other. However, these functions are more difficult to estimate than mono-product functions when the allocation of factors to products is unknown, as is the case here (we know for example the total quantities of feed used in a country, but not those used respectively for rumi and mono). The allocation must therefore be derived from the aggregated estimates, by means of the various available methods (Just et al. 1983; Mishra 2007).

The estimation of such production functions also entails serious risks of biases that are identified in the literature, especially linked to the endogeneity of production factors. The correction of these biases requires appropriate estimation methods. Three estimation methods were selected:

- an autoregressive model that is an effective tool for eliminating autocorrelation (the error term of year t is used as an explanatory variable of year $t+1$),
- a generalised least squares estimation (weighted least squares and two-stage least squares) which substantially reduces the heteroskedasticity bias and, in most cases, gives estimation results close to the autoregressive model,
- different models with fixed effects, which potentially also help to correct endogeneity biases.

This led us to estimate and test various production functions:

- with a variable number of factors $(x_1, ..., x_n)$, and/or of composite indicators combining these factors with other available variables (to account for the quality of pastures in particular),
- with outputs and inputs expressed in the same units, either in total calories or in protein calories[37], especially to capture the “oilcake” effect (soybean cake in particular) which has increasingly become a protein supplement in feeding practices,
- with or without “*trend*” (to assess annual “technical progress”[38]) or temporal and geographical “*dummies*” (to capture the specific effects of certain years or countries),
- with the objective of modelling “geographical” production functions (for instance one function for each MA region) or “typical” production functions (e.g. “intensive-industrial”, “extensive-agricultural”, etc.)
- with different functional forms, especially linear and quadratic.

[37] Reminder: 1 g of proteins provides 4 kcal on average.

[38] Annual production increase not explained by the production factors of the production function.

For the Agrimonde foresight, the following properties were chosen:

- linear functional form,
- geographic functions (one for each of the six MA regions, including 12–40 countries per region),
- with neither *trend* nor *dummies,*
- using protein calories as a working unit; for the simulations, the conversion rates from protein calories into total calories are set equal to the last values observed (2003) but can be modified according to the scenarios (e.g. increase or decrease in the protein content of the feed),
- based on a system of two equations (production of proteins from rumi on the one hand and from mono on the other), with three explanatory factors: proteins from feed (plant and animal origin), hectares of pasture, and level of production of the "substitute" output (production of mono in production functions of rumi, and vice-versa).

These functions make it possible to fairly accurately reproduce the evolution of regional animal production over the past 40 years (Fig. A1.1). More elaborated functions can reproduce these past trends even more accurately, but this was not the major objective here. For the Agrimonde scenarios, the aim was to obtain functions which required a limited number of assumptions to be formulated for the simulations (in Agrimonde, each assumption is subject to time-consuming collective debates), and which tolerated a wide range of variation for the values of production factors (Agrimonde is a scenario-building exercise which can imagine very different worlds from those observed in the past).

The linear form is rather restrictive but is supported by a number of motivations:

- of all the forms tested, it is the most stable in the face of changes in geographical scales[39]; once the production function is estimated with national data, the coefficients of marginal productivity of each factor are valid for the countries of a region and for the entire region,
- the estimated coefficients are closer to physiological coefficients; for example, a coefficient of 0.2 associated with feed (in calories) means that one additional calorie of feed produces 0.2 additional calories of animal product (ruminant or monogastric), which represents a marginal conversion rate of 5 calories of feed per animal calorie; this coefficient is called "marginal productivity"[40],
- the linear form is compatible with a decreasing average productivity of the feed as it is observed empirically (Fig. 2.6). It is also compatible with a substitution between factors and with a substitution between outputs (at a fixed rate).

The generic form of the functions used for the Agrimonde scenarios is presented below (Tables 2.3 and 2.4), as well as their generalised least squares estimation (Tables 2.5 and 2.6). For the simulations, after setting regional quantities of feed and pastures, we solve a system of two equations and two unknowns for each region

[39] Including the Cobb Douglas function with constant returns to scale.

[40] A constant marginal productivity (as the linear form imposes) is a restriction since it does not allow for second order effects to be represented. On the other hand, it makes the model more robust.

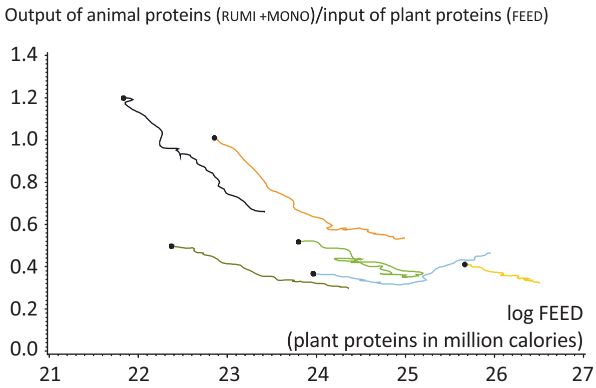


Fig. 2.6 Decreasing average productivity of plant food proteins in the production of animal food proteins (1961–2003). When the value of plant feed is low, the production of animal foodstuffs (*rumi + mono*) relies essentially on pastures, fodders or residues, and the average productivity of feed is then high (i.e. the Output/Input ratio is high). As the relative share of feed in the production increases, its average productivity decreases (the Output/Input ratio decreases). This evolution is generally accompanied by a decreasing share of rumi outputs in the total animal outputs

(prod_rumi and prod_mono). The result of this procedure respects the constraints of the two production functions, but excludes any possibility to fix in advance the rumi/mono proportion in the total amount of outputs. This possibility requires an alternative resolution that also exists in Agribiom, by choosing one or the other of the two production functions.

Interactive Interface and Simulations

One of the main objectives of Agribiom is to facilitate collective debates on past and future production, trade and use of biomass on a global scale, and to promote the emergence of common visions or questions on the past and the future. In order for it to become such a “mediating” tool, a great deal of time and care were devoted to the creation of an interface with Microsoft Access©. By the end of 2008, for various possible scales of geographical analysis (including the six MA regions), this interface was able to:

- show (through graphs) the 1961–2003 evolution of numerous variables obtained from the processing of several million historical data (Chap. 3, Figs. 3.1–3.13, Appendix 2, Fig. A2.1–A2.9), especially the variables or “parameters” which served to simulate the production, trade and use of food biomass,
- describe and test models devised internally (currently, animal production functions), by comparing their results to those observed in the past (1961–2003), by readily changing their coefficients (especially marginal productivities) or mode

Table 2.3 Generic cross-country animal production functions used in Agrimonde

$$prod\_rumi_k = \alpha_0{}^j + \alpha_1{}^j feed + \alpha_2{}^j pastures_k + \beta^j prod\_mono_k$$

$$prod\_mono_k = \gamma_0{}^j + \gamma_1{}^j feed_k + \delta^j prod\_rumi$$

Where:

- k is the country index
- J is the region index
- prod_rumi$_k$ stands for the production of food proteins of ruminants, expressed in kcal per year, for country k
- prod_mono$_k$ stands for the production of food proteins of monogastric animals, expressed in kcal per year, for country k
- $\alpha_0{}^J$ is the constant term (for all countries in region J) of the production function for rumi
- $\alpha_1{}^J$ is the marginal productivity of feed (of both animal and plant origin) in region J, expressed in kcal of proteins of rumi outputs (prod_rumi) per kcal of proteins of feed
- feed$_k$ is the feed use in country k, expressed in kcal of proteins
- $\alpha_2{}^J$ is the marginal productivity of pastures in region J, expressed in kcal of animal proteins per hectare of pasture area
- pastures$_k$ is the surface of the pasture area in country k
- β^J is the substitution coefficient between mono and rumi productions in region J
- $\gamma_0{}^J$ is the constant term (for all countries in region J) of the production function for Mono
- $\gamma_1{}^J$ is the marginal productivity of feed (of both animal and plant origin) in region J, expressed in kcal of proteins of mono outputs (prod_mono) per kcal of proteins of feed
- δ^J is the substitution coefficient between mono and rumi productions in region J

Table 2.4 Generic regional animal production functions used in Agrimonde

$$prod\_rumi_j = \sum_{k \in J} \alpha_0{}^j + \alpha_1{}^j \sum_{k \in J} feed_k + \alpha_2{}^j . \sum_{k \in J} pastures_k + \beta^j \sum_{k \in J} prod\_mono_k$$

$$prod\_mono_j = \sum_{k \in J} \gamma_0{}^j + \gamma_1{}^j \sum_{k \in J} feed_k + \delta^j \sum_{k \in J} prod\_rumi_k$$

where:

- prod_rumi$_J$ is the production of food proteins of ruminants, expressed in kcal per year, for region J
- prod_mono$_J$ is the production of food proteins of monogastric animals, expressed in kcal per year, for region J

of resolution, and by instantly visualising their results with new data or assumptions,

- enter, for a particular scenario envisaged (or one of its variants), the assumptions of parameters and models, and then debate, rework and finalise these assumptions by collectively simulating, with the interface, a global physical balance of the production, uses and trading of food biomass,
- archive the quantitative results obtained with the related assumptions, especially to make them transparent to other parties, and to allow for criticism or more in-depth development of the scenarios and their related assumptions.

Table 2.5 Estimates of cross-country production functions used in Agrimonde: rumi

	OECD	ASIA	LAM	SSA	FSU	MENA
$\alpha_0{}^J$ (Intercept)	+251,075,226.1	+20,528,324.9	+5,903,806.83	−2,668,975.75	+42,720,057.2	+19,928,565.5
$\alpha_1{}^J$ (feed)	+0.3 9***	+0.17***	+0.25***	+0.34***	+0.26***	+0.24***
$\alpha_2{}^J$ (pastures)	+6,411***	+3,000***	+12,881***	+3,349***	+2,758***	+4,081***
β^J (prod_mono)	−1.89***	−0.01***	− 0.23***	−0.05***	−0.01***	−0.87***

*** significant at the 1 % level

Table 2.6 Estimates of cross-country production functions used in Agrimonde: mono

	OECD	ASIA	LAM	SSA	FSU	MENA
$\gamma_0{}^J$ (Intercept)	−16,343,932.5	−295,377,986	+1,749,430.94	+1,001,663.42	−368,017.209	+12,688,321.3
$\gamma_1{}^J$ (feed)	+0.15 ***	+0.39***	+0.21***	+0.18***	+0.08***	+0.16***
δ^J (prod_rumi)	−0.14 ***	−0.53***	−0.05***	−0.05***	−0.01***	−0.29***

*** significant at the 1 % level

The interface is organised into several windows or "parameterisation domains" (human populations, food consumption, land occupation, food production and productivity, food trade, food uses, animal production models, etc.) which make it possible to visualise historical data in each of the domains concerned, and then to register (or calculate), in each of these domains, values of scenarios (or variants of scenarios) on a specific timeline. A particular window can be used to:

- recapitulate, for each region of the world under consideration (here, MA zoning) and on the selected timeline, the main assumptions formulated for the scenario (populations, diets, land use, etc.) and their implications in terms of use, production and net trade (in Gkcal/day) for the five food biomass compartments (vege, aqua, mari, rumi, mono),
- adjust these assumptions until a physical balance between the uses and resources of food biomass is obtained on a global scale, some of these adjustments requiring the use of other Agribiom tools in order to be carried out correctly, especially as regards animal production[41].

A simulation via the Agribiom interface consists in illustrating a balance (or an imbalance) between the uses and resources of food biomass, considered by region and then globally. For each region considered, this illustration implies a specification of assumptions: 1) on the elements of our resource-use equation (see food biomass resource-use balances p. 36)[42], 2) on the models used to provide some of these elements (here, animal productions), and 3) on international trade, especially on the regional preferences for acquiring resources abroad (is there a preference for importing animal feed or animal products themselves? Which region could preferably supply them? etc.). When these assumptions are not all compatible, or to simulate the impact of a modification to one of them, adjustment criteria must be defined to select those variables which will be adjusted and those which will not.

In an economic equilibrium model such as IMPACT (IFPRI, International Food Policy Research Institute), the rules of adjustment are explicit and exogenous. The authors know them before carrying out a simulation. They are defined by a set of elasticities and constraints on certain physical or economic variables which lead to supply and demand functions. On the other hand, the quantities (production, consumption, surfaces, etc.) and equilibrium prices are generally endogenous. A difficulty often mentioned in these models probably stems from the choice of elasticities, that is, parameters which represent agents' reactions to

[41] Note that in its 2008 version, the Agribiom interface does not yet allow the assumptions and physical balances obtained to be associated with certain evaluations pertaining, in particular, to energy or water consumption, employment in agriculture, greenhouse gas emission or sink, etc. This was initially, and is still is, an objective.

[42] Except for stock variations which, for the simulation of the base year (e.g. 2003) chosen to serve as a reference for the study of other simulations, are integrated into a use section called "Residue". This "Residue" section also enables us to integrate amounts linked to statistical errors or inaccuracies found in the past (see food biomass resource-use balances); amounts without which there would not be a perfect equilibrium between resources and uses, and without which the comparisons of simulations then carried out would be biased.

variations in the economic environment (by how much does the wheat supply increase in a particular region when the wheat price increases by 1 %; by how much does consumption decline if the price in the region increases by 1 %; by how much does wheat consumption increase when the income of the region rises by 1 %, etc.). These elasticities are expected to provide stereotypical reactions of production and consumption to price variations or to variations of price-like economic variables (especially income). They have the important quality of making it possible to simultaneously implement many decentralised adjustments, while maintaining an economic equilibrium between supply and demand. Thus, an unsatisfied demand would be translated endogenously by a price increase that would trigger both an increase in production and a drop in consumption. The equilibrium between supply and demand is thus constantly guaranteed by price adjustments, and the (solvent) demand is always satisfied, by construction. But this category of models is not suited to representing a world geared towards the satisfaction of needs (physiological, social, environmental necessities, etc.); in this type of modelling, it is not for example certain people's lack of food nutrients (non-satisfaction of a need) that increases production, but the non- satisfaction of their demand, which depends on their purchasing power, preferences, and information.

In the Agribiom simulations, the quantities and other physical values are exogenous (i.e. chosen by a person or an expert panel). With each set of assumptions, we find a certain disequilibrium, with its distribution by region and biomass compartment. This disequilibrium is the endogenous (and relevant) information from the simulation. Based on this disequilibrium, there is an infinite number of ways of making an adjustment since, in practical terms, each element of the choice is continuous. From this point of view, the path proposed by the panel for reaching a balance, consisting of the alteration of certain elements by trial and error, following certain rules[43], defines a set of adequate conditions to obtain a resource-use equilibrium. It may also be useful, for the analysis, not to automatically balance the economy in order to show regional surpluses and deficits, and collectively to debate the different ways or conditions for remedying the deficits. One can also debate how needs can be met by simulating extremes: for example, an increase in demand can trigger an increase in yields without an increase in the cultivated area, or vice-versa. Extreme answers are probably not the most realistic, but they can be very valuable in a scenario-building exercise.

Thus, the added value of the Agribiom interface resides in learning the role of all the variables, models and decision-making rules used to achieve a global balance, and not only in the final image of the resource-use balance proposed at the end of the process. It is in this sense that the interface is interactive, and that it can only really function through interaction.

[43] Example of rules: (1) if a region faces a shortage in food calories, it imports the plant products necessary to cover the food needs of both humans and animals (i.e. domestic production of animal products with some imports of plant feed, instead of direct imports of animal products); (2) the imports come from the largest surplus regions, in decreasing order of their surplus quantities; (3) if total regional surpluses cannot cover total regional shortages at the global level, some exogenous variables are adjusted upwards (yields, cultivated areas, etc.) and not downwards (diet etc.).

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