Trends in global meat consumption and its impact on international trade, agricultural land use, and the environment

A scoping paper for the European Forum on Integrated Environmental Assessment (EFIEA)[1]

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1 Introduction

This paper provides the background for developing a research and policy advice agenda on the global food system for the European Forum on Integrated Environmental Assessment (EFIEA). The example of meat will be used for demonstrating the environmental effects of different consumption patterns and lifestyle choices. In the first chapter, the importance of food consumption and agricultural production from various perspectives will be highlighted, and several strategic policy questions will be derived. In the second chapter, an overview of current research related to long-term projections on food and agriculture will be given, including the status of general scenario building, specific aspects of food demand and agricultural supply, a summary of existing research initiatives in the area of integrated modelling of food issues, and the status of data availability relevant for this research. Finally, a preliminary agenda for integrated assessment research and policy advice on meat demand, agricultural production and international trade is developed.

1.1 Does nutrition matter?

Economic relevance

From the perspective of the rich, industrialised countries, the importance of the agriculture and food sector has constantly decreased over the last decades. The share of agriculture and food in overall GDP is falling and it is below 5 percent now in most industrialised countries. The same applies to the share in total labour force. To give an example, the number of farms in Germany has dropped from about 2 million in 1950 to less than half a million now. Less than 5 percent of the workforce is now employed in agriculture, as wage levels and working

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conditions are more attractive in the manufacturing and service sectors [1]. At the same time, farm size has increased, agricultural production has become more capital-intensive and highly mechanised. Moreover, as average per-capita income rises, the relative share of total household budgets spent on food continues to fall and has reached levels around 10 percent in the richest countries. So, many people in high-income countries may wonder, why research on nutrition and agricultural production might be relevant at all.

From the perspective of most developing countries, the picture is quite different. In most poor countries domestic agricultural and food production is not only important for food security and health, it is at the same time the major type of employment and source of household income. Many economists claim that there is no way out of poverty, except through agricultural and rural development [2]. Due to high population growth in poor countries together with an increasing degree of urbanisation, the role of agriculture, food production and food distribution in overall economic development is even likely to rise in the future. Hence, in many countries the agriculture and food sector remains an important part of the economy.

Environmental relevance

Human activity has become a major factor shaping environmental conditions on a global scale. Population growth translates itself through consumption patterns into pressure on natural resources like land, water, air, biodiversity, or minerals. A large share of these environmental pressures is directly linked to the consumption of food and the production of agricultural raw materials. On a global scale, agricultural production accounts for about 40 percent of total land use, it uses about 70 percent of all freshwater withdrawals for irrigation, it contributes significantly to climate change through methane emissions, and it is considered one of the most important causes for biodiversity loss [3]. This applies, with regional differences, to rich and poor countries alike.

From an environmental point of view, the consumption of animal products, and meat in particular, implies a rather inefficient use of natural resources for the production of food energy and proteins. Land and water requirements for producing a given amount of calories for human consumption in the form of meat and the related animal feed by far exceed the input demand of a vegetarian diet. In regions with favourable natural conditions for food production this may not matter, but in countries already facing water scarcity or vulnerable soil conditions this could be important, especially as water demand for household and industrial uses will also rise strongly in the future. The conflict between agricultural production and the protection of key environmental resources, i.e. how to produce sufficient food for a growing world population in a sustainable way, is far from being resolved in any country.

Health relevance

Nutrition has a significant impact on human health and well-being. Chronic under-nourishment is obviously unhealthy, especially for small children. But also problems related to excessive or unbalanced consumption of food are not to be neglected. In fact, obesity is being observed at an increasing rate not only in high-income countries, but also in developing countries, especially among the urban population. As per-capita income rises, the share of animal products, especially animal fats, in human diets tends to increase. In most industrialised countries, the level of fat consumption has meanwhile exceeded the healthy limits as suggested by the World Health Organisation. So, in principal it should be in people's own interest to limit their meat consumption. However, a serious lack of dietary consciousness and nutritional education can be observed in most societies.

Cultural relevance

While dietary choices and especially meat consumption are strongly determined by per-capita income levels, socio-cultural traditions and habits do also matter. In some societies, meat consumption is restricted by religious rules. India is a good example where less than 10 percent of total calorie intake is based on animal products [4]. In most societies, however, the consumption of meat demonstrates a certain social status and it is an important aspect of the overall lifestyle pattern. On average, at very low income levels meat consumption plays only a minor role due to household budget constraints. Beyond a certain income level, meat consumption rises together with income at a fast rate, and it is usually considered as an inevitable part of a healthy diet. Eventually, a level of satiation is being reached where meat does no longer represent prestige or social status. Quite the opposite, in certain high-income social groups intensive meat consumption is being blamed for health risks, overweight and an unsustainable lifestyle.

Policy relevance

Agriculture and food production are highly policy relevant on a global scale. Almost all countries in the world have more or less distorting policy interventions in place in the food sector, New Zealand being one of the few exceptions. Originally these policies were motivated by concerns about national food security and self-sufficiency as well as providing farmers with stable incomes in view of volatile market conditions. After several decades in place, agricultural policy measures are now subject to strong lobbying efforts by various interest groups, although most of these measures have been proven ineffective in achieving their intended goals. Moreover, agricultural policies in industrialised countries tend to harm poor countries by preventing economic development through agricultural production. The total amount of subsidies transferred to farmers in rich countries is around 300 billion US$ per year, which can only be fully appreciated when compared with the global sum of development aid payments to the poorest countries, which amounts to only about 50 billion US$ per year. Moreover, the issue of agricultural subsidies is at the core of international trade negotiations in the Doha round of the World Trade Organisation. It is not unlikely, that disagreement in this area will seriously delay or even prevent the establishment of a more efficient global trading system, which could be important not only for economic development but also for more efficient use of land and water resources on a global scale.

Research relevance

For the reasons mentioned above, the agriculture and food sector may provide a useful "case study" for the integrated assessment of broader issue which come about in the process of achieving a sustainable development. Consumer choices and preference changes with respect to food, e.g. the choice between a vegetarian and a meat-based diet, can be taken as an example for other environmentally relevant lifestyle and demand phenomena. Regional food demand in connection with the internationalisation of the food industry and global trade may represent the type of teleconnections and globalisation forces which prevail in most economic sectors nowadays. Agricultural production can be taken as a prime example for technological change and induced innovation as well as for studying the interactions between society and nature around the appropriation of natural resources for the production of goods for human consumption. To summarize, it can be said with assurance that agriculture and food matter for various reasons in almost all countries, and overall economic growth will not eliminate nutrition issues [2].

1.2 Strategic policy questions

Proceeding from the proposition that nutrition matters for various reasons, the following strategic policy questions can be formulated, which will in subsequent sections be elaborated into a set of research questions.

1. What determines the demand for animal products and especially meat in different world regions and over time? How do people's *preferences and lifestyles change* over time and how do these patterns diffuse globally? What role can and should policy play

in view of diet-related health problems and increased awareness of food safety aspects?

2. What are likely scenarios for the development of global food demand with a special focus on animal feed and meat? Which parameters and biophysical conditions may determine *limits to the global supply of food*, especially with respect to land and water resources? Are there well-defined guardrails for natural resource use which should not be surpassed, even given the expected strong population growth? How can and should policy efficiently intervene in these long-term developments?
3. What types of *substitution possibilities* for meat, e.g. novel protein food, may emerge in the future and how do they affect the adaptive capacity of human society to growing environmental pressures? What is the potential of *technological progress* to mitigate the impact of agricultural and food production on natural conditions? What are the endogenous processes driving the required innovations? How should governments support agricultural research?
4. Apart from technological change and economic growth, what *changes in the institutional framework* of food consumption, production and trade are required to prepare human society for the upcoming challenges? How can *global trade negotiations* within the WTO be framed to focus more strongly on global equity and distributional concerns in view of 800 million malnourished people worldwide?
5. In order to prepare viable transitions to a sustainable global food system, what kind of *improved observation and monitoring systems* are required to provide appropriate data and information for enhanced analysis and understanding?

2 Current status of research

2.1 Global food scenarios

Population growth

World population growth is likely to come to an end in the foreseeable future. According to a recent study, there is around an 85 percent chance that the world's population will stop growing before the end of the 21st century. Furthermore, there is a 60 percent probability that the world's population will not exceed 10 billion people before the year 2100. For different regions, the date and size of the peak population will vary considerably. The median projection for world population in the year 2050 is 8.80 billion, with an 80 percent prediction interval between 7.3 and 10.4 billion [5].

Optimistic vs. pessimistic views

Whether food production can keep pace with the demand for improved diets for a rapidly growing world population is a question that has been debated vigorously since it was raised by Malthus two centuries ago. Although much of mankind has experienced improvements in diets over the past century, expert views about prospects for the coming decades differ as sharply as ever [6].

There is a rather optimistic group consisting primarily of economists and modellers in the neoclassical tradition. They note the relatively low crop yields, inefficiencies throughout the food production and consumption chain, and the ample reserves of potential arable land in many developing countries. They further hold the view that sounder government policies, wider application of green revolution technology, reduced inefficiencies, upgraded rural infrastructure, and greater investments in human resources and research will make much larger harvests possible and no insurmountable environmental constraints are foreseen [7-10].

The rather pessimistic group primarily belongs to the ecology and ecological economics communities focussing on carrying capacity of the Earth. They point to the many signs of environmental stress and the increasing difficulties encountered in expanding agricultural land, water supply, and crop yields, and in controlling pests. In their view a large expansion of agricultural output is not feasible, and they even doubt whether current levels of crop production can be sustained in a number of countries. Global warming would impose further stress on agricultural systems, the prospects for increased food production would become even less favourable than they are at present. A major expansion of food supply would require a highly organized global effort by both the developed and the developing countries that has no historic precedent [3, 11].

Supply vs. demand effects

In the debate about global food security over the next century there is a clear focus on supply-side effects and developments, i.e. technological change in agricultural production, limits to natural resource availability and resource quality, most of all agricultural land and water for irrigation. Surprisingly, the importance of changes in demand growth and demand structure have been studied to a lesser extent. In many scenarios, the current trend towards higher meat consumption at higher income levels is simply extrapolated over a wide range of countries on a global scale in the course of economic development. However, there may be significant scope for altering the relationship between income and food demand. For example, changes in dietary structures may evolve due to increasing knowledge and concerns about health impacts of alternative diets or reduction of waste and other efficiency changes within the food system [12]. These demand-side effects could have a significant impact on the outcome of long-term global food scenarios (Table 1).

Table 1: Conservative estimates of efficiency gains in global food production achievable by the year 2050

	Changes compared to 1990 practices	**Gains equivalent to global 1990 food energy consumption (percent)**
Improved field efficiencies	Better agronomic practices (raise average yields by 20 %)	22
	Higher fertilizer uptake (raise nutrient use efficiency by 30 %)	7
	Reduced irrigation waste (raise water use efficiency by 30 %)	7
Reduced waste	Post-harvest losses (lower by 20 %)	6
	End-use waste (lower by 20 %)	8
Healthier diet	(Limit fat intakes to 30 % of total energy)	10
Total gain		60

Source: [13]

Medium-term vs. long-term perspective

Most scenarios and analyses on the development of the global food system cover the period up to 2025 at most [7-10]. From a social science point of view the time span of one generation is already very long and it may be questionable whether model simulations and scenario analyses beyond two to three decades are possible and have any meaning [13]. A few such analyses beyond the year 2050 have been conducted mainly with respect to the impact of climate change on agricultural production, as significant changes in the global climate system are not to be expected before the middle of the 21st century [14, 15]. Like long-term environmental changes, profound alterations in cultural habits and dietary preferences may also come about only within several decades, so there may be scope for longer-term analyses from this perspective as well.

Institutional issues and regional characteristics

When global assessments of food supply and demand are conducted, institutional issues and regional characteristics are often overlooked. Even if enough food is in principle available in poor countries, it might not be accessible for certain population groups due to lack of income or infrastructure. Furthermore, even if appropriate food is accessible to most population groups, it might still not be fully utilised for improving the nutritional status. Malnutrition, like deficiencies in micronutrients or obesity, do occur at all income levels. So, *availability* of food is only a necessary condition for improved nutrition. *Access* in terms of income and nutritionally appropriate *utilisation* of food are equally important.

The same regional disaggregation is required with respect to the role of international trade for improving the efficiency of the global food system. If countries, which are principally in need of food imports, do not reveal an effective demand for food due to lack of foreign exchange earnings from non-agricultural sectors, the importance of trade for improving food security may be overestimated. That is to say that world market prices do not reflect adequately the problems of the poor and the food insecure [2].

2.2 Dietary choices and food demand

Much of the past discussion about global food problems has focused on available means to expand the supply of agricultural products. Demand measures have been given less attention, even though they could make substantial contributions. Diets are largely determined by economic factors, particularly prices and incomes. As income rises, people tend to consume more calories in total, and the share of animal calories increases, especially the consumption of animal fats. In Africa people derive two-thirds of their calories from starchy staple foods and only 6 percent from animal products. In Europe people derive 33 percent of their calories from animal products and less than one third from starchy staples. The average global diet falls somewhere in between these two extremes (Table 2) [16].

Table 2: Major sources of food energy in industrialised and developing countries (1994, percent share)

Product group	Industrialised countries (Percent share)	Developing countries (Percent share)
Cereals	31	56
Meat and dairy products	28	12
Sweeteners & vegetable oils	23	17
Roots and tubers	4	5
Others	14	10

Source: Adapted from [16].

Diets in part of the rich world with a large proportion of animal products are now considered to be detrimental to health. A satisfactory food energy availability is about 2900 kcal per capita per day. A supply of 2900 kcal is midway between the level in the United States (3750 kcal), where over half the adult population is overweight, and that in North Korea (2100 kcal), where half the population is undernourished. With respect to the minimum daily consumption of animal protein opinions differ. According to some recommendations only about half of the protein in the diet should come from vegetable sources, which would imply that about 40 g of animal protein per day are required for a satisfactory diet. As this corresponds to approximately 740 kcal of livestock products, their recommendable share in total daily calorie intake would be approximately 23 percent [17].

Furthermore, the WHO recommends to limit dietary intake of fat to no more than 30 percent of calorie consumption, which may be even revised downwards in the future. Efforts to reduce this proportion are underway and health concerns in rich countries have begun to lead to declined beef consumption in a number of countries since the mid-1970s. However, overall meat consumption has remained approximately constant, as people shifted to eating poultry [6, 18].

As most developing countries in the future are likely to follow the trends in rich countries, global meat consumption can be expected to rise strongly over the next decades, due to a combination of population growth, growth in per-capita income and a high income elasticity of meat demand. Annual growth rates of aggregate meat consumption until 2030 are estimated between 1.4 and 3.0 percent. This would imply an increase in average global meat consumption per capita from 32.6 kg/year to 44-54 kg/year, depending on different growth assumptions [19].

Another important trend is related to urbanisation and its effect on dietary structure. In 2025 about two thirds of the world population is expected to live in urban conglomerates, rising from about 45 percent in the late 1990s. This demographic change is even stronger in less developed countries. As people are moving into urban areas, they tend to change their professional occupation and physical activity, which in turn leads to a shift in diets. Not only do the shares of animal fats and sweeteners increase strongly with income levels, they are even further increased in an urban environment. This is one of the reasons for increased relevance of obesity in countries with relatively low income levels. Together with additional logistical challenges these issues have to be further explored with respect to the emergence of a larger numbers of so-called mega-cities [20-22].

Changes in dietary structures may also be influenced by the availability of new food products. If the food industry came up with attractive novel protein food based on pulses, consumers may be willing to substitute these new products for meat. The potential of this type of technological change in the food industry, the impact on the global demand for animal feed, and the substitution potential in average diets is the research focus of the PROFETAS[2] project [23].

2.3 Food supply and resource use

In view of the described rapid developments on the demand side, it is heavily debated whether global food supply will keep up with this pace or whether farming activities will run into serious conflict with the concurrent goal of preserving local environmental conditions, which continue to provide the life support systems for future generations. In the past, agricultural production could rely on virtually costless water supplies as well as available land for expansion. Meanwhile, most of the potentially available arable land is already under cultivation and future production increases will have to be achieved through more intensive production technologies on the given area of land. However, improper management and irrigation techniques have already caused serious land degradation on a large scale. In the future, agriculture will have to compete for water and land with other economic activities, like urban development, industrial use, forestry, and nature conservation [3].

With respect to future yield increases one can take an optimistic view and assume that past trends in agricultural productivity growth will continue for some time. Some model calculations show that even at conservatively reduced growth rates, global food supply will outpace demand up to 2020 and real prices for agricultural commodities are likely to continue to fall [8, 24]. However, the assumption of exponential growth paths instead of logistic curves has been questioned. This distinction will become even more important in the very long run [25, 26]. The potential of biotechnology and genetic engineering for accelerating agricultural productivity growth is still very unclear and subject to a strong public debate. Some initial trials show positive effects, but environmental consequences have to be further investigated and widespread social acceptance remains questionable [27].

Land use

The amount of land necessary for the production of various food items differs widely, especially for animal products. Different animals have different feed requirements and feed conversion rates (Table 3) [18].

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[2] Protein Foods, Environment, Technology And Society: www.profetas.nl

Table 3: Conversion rates of grain to animal products

Animal product	Kg of feed / kg of output	Kcal of feed / kcal of output
Beef	7.0	9.8
Pork	6.5	7.1
Poultry	2.7	5.7
Milk	1.0	4.9

Note: These conversions are very approximate, as the caloric density of both feeds and animal products can vary greatly. Furthermore, data units are often not specified or precisely comparable.

Source: [18]

This directly contributes to the area of land required for certain food products (Table 4) [28]. However, it has to be considered that the required quality of land differs for various livestock production types. For example, ruminants like cows and goats are able to convert grass from permanent pasture land into valuable food for human consumption, but cattle can also be fattened on a feed mix with a large share of cereals. Pigs can be raised primarily on grains, but also on human food residuals. Hence, the amount and quality of land required for livestock production depend very much on the specific production systems.

Table 4: Specific land requirements per food item (Netherlands, 1990, $m^2*year*kg^{-1}$)

Food item		Specific land requirement ($m^2*year*kg^{-1}$)
Fats	Vegetable oil	20.7
	Low fat spread	10.3
Meat	Beef	20.9
	Pork	8.9
	Chicken filet	7.3
Milk products and eggs	Whole milk	1.2
	Cheese	10.2
	Eggs	3.5
Cereals and other crops	Cereals	1.4
	Sugar	1.2
	Vegetables (average)	0.3

Source: Adopted from [28]

The total amount of land available for agriculture not only depends on biophysical conditions, but also on the demand for land for other economic and environmental purposes. Infrastructure development and urbanisation may reduce agricultural areas around the major population centres. In the course of a major energy transition there might arise a significant demand for bio-fuel production not only from fast growing forests, but also from agricultural crops. Moreover, a certain share of land may have to be set aside for nature conservation and biodiversity management, in order to maintain nature's basic life supporting functions [15, 29].

More intensive production systems may lead to land degradation, if they are applied year after year on the same area. Main types of land degradation are soil erosion from wind and water, chemical degradation (e.g. nutrient loss, salinisation, pollution), and physical degradation (e.g. compaction, water-logging). Land degradation is a very important issue in some geographic regions, but it remains unclear whether it may become a serious threat to global food supply [30, 31]. While in some parts of the industrialised world problems of fertilizer overuse, like nitrate leaching and eutrophication, are of considerable concern, in many developing regions, like Sub-Saharan Africa, inadequate replenishment of removed nutrients reduce soil fertility and increase erosion. Hence, in order to assure sufficient nutrient supply for more intensive production on a global scale, the demand for fertilizer will rise. Especially nitrogen requirements will increase significantly, according to some estimates to 50 percent above current consumption by 2050. What this means for sensitive environmental systems and the nitrogen cycle, which is as yet neither well observed nor understood, remains unclear [8, 17].

Water use

The resource base that may pose the most serious limitations to future global food supplies is water. Irrigated area accounts for nearly two-thirds of world rice and wheat production, so growth in irrigation output per unit of land and water is essential to feed growing populations. Since the development of traditional irrigation and water supplies is increasingly expensive and new sources like desalination are not expected to play a major role soon, water savings at every level are absolutely necessary. Crop output per unit of evaporative loss has to be increased and water pollution has to be reduced. However, the size of potential water savings in agricultural irrigation systems is unclear. While specific water uses can be made more efficient through better technology, especially in many poor countries, the potential overall savings in many river basins are probably much smaller, because much of the water currently lost from irrigation systems is re-used elsewhere. Increasing water demand from households and industry will further exacerbate the challenge [32, 33].

The specific water requirements for various agricultural products differs widely, from less than 200 litres per kg output for potatoes, sugar beets or vegetables, to more than 1000 litres per kg output for wheat and rice [34]. A typical diet with meat consumption at American levels requires about 5400 litres of water for crop evapotranspiration, while a comparable vegetarian diet requires only about half the amount. In comparison, the daily amount of water required for drinking and sanitary purposes is almost negligible at less than 60 litres. The future global challenge with respect to agriculture and water implies that over the next 25 years food production has to be increased by about 40 percent while reducing the renewable water resources used in agriculture by 10-20 percent [35, 36].

Regional limitations to water availability may be partly overcome through increased international trade in food products and the incorporated "virtual" water. The strategy for a water-scarce country could be to import water-intensive products and export goods which require less water for their production, and thus relieve the pressure on national water resources. However, in a global economic system food importing countries then have to develop export capacities to raise the required foreign exchange earnings [37].

Climate change

An additional constraint to agricultural production in the long run, i.e. in the second half of the 21st century, may occur through global climate change. A rise in atmospheric CO_2-levels and a corresponding rise in global temperatures will not only affect plant growth and yields, but also alter the regional patterns of precipitation and water availability as well as land erosion and fertility. Sensitivity studies of world agriculture to potential climate changes have indicated that global warming may have only a small overall impact on world food production because reduced production and yields in some areas are offset by increases in others. However, regional impacts vary quite significantly, with tropical regions especially suffering from droughts. Moreover, the combined effects of various changes in the long run are still highly uncertain [38].

Institutional framework

Apart from technical and environmental constraints, a further set of limitations to increased agricultural production is given by institutional constraints. If the world fails to meet its food demands in the next half-century, the failure will be at least as much in the area of institutional innovation as in the are of technical change. The design of institutions capable of achieving compatibility between individual, organisational and social objectives remains an art rather than a science. As one author puts it, “at our present stage of knowledge, institutional design is analogous to driving down a four-lane highway looking out the rear-view mirror. We are better at making course corrections when we start to run off the highway than at using foresight to navigate the transitions to sustainable growth in agricultural output and productivity" [39].

2.4 Integrated modelling and assessment activities on food issues

A more comprehensive analysis and understanding of the world food system can draw upon a substantial number of existing research projects and initiatives in the area of integrated assessment and modelling. The following projects cover various specific aspects of agriculture and food in different thematic contexts.

Climate change and agricultural land use

Research groups with a focus on the analysis of energy systems and climate change include the IMAGE[3] project as well as the ICLIPS[4] project [40], where greenhouse gas emissions of different land use patterns as well as the potential of bio-fuel production on agricultural land as an alternative energy source have been analysed [15]. The US Department of Agriculture has developed its FARM[5] model, a computable general equilibrium (CGE) model with a focus on the interaction between climate change, economic growth, agricultural production and environmental resource use.

International agricultural trade

The GTAP[6] consortium has developed a CGE modelling framework as well as a database for global economic analysis, but is also beginning to extend its focus towards agricultural resource use, especially land use issues. The International Institute for Applied Systems Analysis (IIASA) maintains a global CGE modelling framework called Basic Linked System (BLS) which has been applied to various questions on global environmental change [41]. The International Food Policy Research Institute (IFPRI) has a long tradition of partial equilibrium agricultural trade modelling with its IMPACT[7] model [8].

Integrated modelling of agricultural land and water use

Recently the IMPACT model has been coupled with the global hydrological model WaterGAP[8] in order to come up with more reliable global projections for water demand and supply

[3] Integrated Model to Assess the Greenhouse Effect: http://sedac.ciesin.org/mva/image-2.0/image-2.0-toc.html
[4] Integrated Assessment of Climate Protection Strategies
[5] Future Agricultural Resources Model: www.cru.uea.ac.uk/link/hadcm2/abstracts/darwin_paper.html
[6] Global Trade Analysis Project: www.gtap.agecon.purdue.edu
[7] International Model for Policy Analysis of Commodities and Trade
[8] Water – Global Analysis and Prognosis: http://www.usf.uni-kassel.de/usf/mitarbeit/homepages/doell/research3.htm

[42]. IIASA has linked the BLS model with its agro-ecological zones (AEZ) model to assess future changes in global land use and land cover [43]. On a more regional scale, a group at IFPRI has applied an integrated economic-hydrologic river basin model to the Maipo River Basin in China [44]. Within the GLOWA[9] project a multiple-agent modelling framework has been used to analyse agricultural production, land use patterns and water management in the Volta river basin in West Africa [45].

Another starting point to improve the understanding of society-biosphere interactions is the extension of existing biosphere models. Two projects have recently started to integrate human activities into the LPJ dynamic global vegetation model[10]: the ECOBICE[11] project and the ARIES[12] project. The aim of these groups is to come up with a coupled climate-biosphere-economy modelling framework, including the global water cycle, in order to model the interfaces between the various sub-systems more consistently than in the past.

As the attempts to combine models from various disciplines grow, there is an increasing need for a systematic treatment of model interfaces and information exchange. Recently there has been a proposal to develop a modular approach to integrated assessment, based on advances in knowledge management as well as in object oriented software engineering. The goal should be to develop a community pool of integrated assessment modules, along with software and know-how for running them in varying combinations [46].

2.5 Data sources on global food issues

The understanding of the global food system can only be substantially improved, if a consistent, continuous database with global coverage is available, especially for modelling purposes. The most widely used official data source on agriculture and food are the FAO statistics. For example, the FAO food balance sheets provide detailed information on the share of calorie consumption derived from livestock products vs. crops over the last decades. Although generally acceptable, there has been criticism with regard to the measurement of food availability and nutrition problems. It has been claimed that the food balance sheets do not correspond to comparable information from food intake surveys, and the estimations on the number of malnourished people might be misleading [13, 47]. Moreover, important monetary information,

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[9] Global Analysis of the Water Cycle: www.glowa-volta.de/land/sub_l3.htm
[10] Lund-Potsdam-Jena model: www.pik-potsdam.de/~wlucht/lpj/index.html
[11] Economy-Biosphere-Climate: http://ecobice.uni-oldenburg.de/
[12] Analytical Research on Interconnections between Ecosystems and Society: www.pik-potsdam.de/~wlucht/aries/aries_main.html

like food expenditure shares for a large number of countries calculated in a consistent way, is currently lacking.

As mentioned above, the GTAP consortium has synthesised a database from a wide range of international sources on national accounts, global trade flows and policy intervention measures. This harmonised database now covers 66 regions and 57 economic sectors worldwide, mainly for the purpose of general equilibrium trade modelling.[13] Another valuable source for information on agricultural policy intervention and trade distortions is the Agricultural Market Access Database (AMAD)[14], which is a joint effort by several international organisations, like the EU, OECD, World Bank, UNCTAD, etc.

For more in-depth analysis of the links between agricultural production and natural resource use, available economic accounts and monetary flows will have to be linked more closely with measurements on physical material and energy flows. This becomes especially relevant when natural resources are not adequately priced or not valued in monetary terms at all, as it is widely the case for irrigation water. Attempts to systematically link standard social accounting matrices with physical input-output tables have just begun for selected countries. On the international scale, the measurement of "virtual water flows" incorporated in agricultural products is another new research direction [37, 48].

A promising way for improving the information base on regional environmental pressures is the increasing use of spatially explicit and gridded data. As the impacts of agricultural land and water use crucially depend on specific regional conditions, the combination of e.g. satellite remote sensing information with official statistics or survey data can lead to much more specific insights. The Center for International Earth Science Information Network (CIESIN)[15] has started to pool various global datasets in gridded form. For example, gridded information on land use and population density could provide a valuable data source for future integrated modelling efforts on regional food demand and its environmental consequences.

In addition to official statistics and spatial information with global coverage, sample surveys will be necessary to complete the picture about regional specifics on food consumption, production and the environment. Most survey studies are only done for selected countries or regions and often not in a repeated form. However, a few initiatives have prepared infrastruc-

[13] http://www.gtap.agecon.purdue.edu/databases/v5/default.asp
[14] http://www.amad.org
[15] http://www.ciesin.org/index.html

tures which may be used for systematic and continuous sample surveys on food-related issues with global coverage in the future.

The World Value Survey[16] conducts representative surveys on personal values and beliefs in an increasing number of countries, now covering about 80 percent of the world's population. This investigation is currently conducted for the fourth time since the early 1990s. A similar endeavour, although more specifically targeted to food questions, is the Food Issues Monitor by Environics International, a social research company with a special focus on environmental topics.[17] In the area of public health monitoring the INDEPTH network[18] has established a set of 29 regional investigation centres in Latin America, Africa and Southeast Asia, for which a common protocol for the collection of health-related social and economic parameters is being developed. Close collaboration with local experts is considered a key success factor for deriving reliable and representative information. With regard to international comparison of agricultural production costs and regional farming systems the International Farm Comparison Network (IFCN)[19] has started to collect farm accounting data for major production areas in different continents. The main purpose of this initiative is to compare production costs and international farm competitiveness. But it could probably also be used for determining environmental effects of different local production systems.

Many of these available data sources have been used by numerous initiatives to develop indicators for measuring sustainability. Within some of these indicator sets, topics like reduction of hunger and poverty and monitoring of changes in land and water use are directly linked to agriculture and food [49].

All these existing activities could provide important building blocks for a global network for integrated monitoring and assessment of regional aspects of the global food system. If the sample sites are chosen carefully as to cover the whole range of regional characteristics and regional hotspots with respect to environmental and social pressure, in the long run such a monitoring system may be able to reveal successful patterns of sustainable development. However, this will only be achieved if regional case studies are subject to a common research protocol, if various topics and methods of investigation are applied in a truly comparative manner, and if these case studies are continued over a long time period. This is the core idea

[16] http://wvs.isr.umich.edu/index.html
[17] http://www.environicsinternational.com/sp-fim.asp
[18] http://www.indepth-network.net
[19] http://www.ifcnnetwork.org/

brought forward within the Sustainability Geoscope[20] initiative, which aims at developing a global monitoring system for supporting the management of transitions towards sustainable development [50, 51].

3 Research scope and policy advice agenda

Truly integrated assessments of food consumption, global food trade, agricultural production and resource use as well as agricultural policies are as yet largely underdeveloped. On the one hand, agriculture and food issues are often studied from a rather narrow disciplinary perspective, e.g. agronomy, agricultural economics, nutrition science or economic development. On the other hand, integrated assessment projects have so far largely focussed on questions concerning the energy sector and global climate change, where agriculture is only part of the problem and plays a minor role in the investigations. However, as mentioned in the first section, the agriculture and food sector could provide a valuable "case study" for more general interactions of economic, social and environmental factors, if all relevant aspects are taken into account in an integrative way. These are ranging from lifestyle changes and consumer preferences to agricultural production technology and its environmental consequences, including institutional frameworks like the international trading system and national policies regarding agriculture and the environment. Integrated assessment methods have the potential to provide a more comprehensive picture and a better understanding of the global system of agricultural production and food processing, trade and consumption. This is a prerequisite for the design of improved policy measures that could provide the institutional framework for reduced hunger, improved nutritional education, fewer diet-related health problems, more efficient agricultural trade, environmentally sound agricultural production technologies, and sustainable rural development.

An integrated assessment of global trends in meat demand and its impact on international trade, agricultural production and related environmental consequences has not only a high policy relevance, it also provides theoretical challenges, a demand for improved integrated modelling tools as well as the necessity for a critical assessment of the available data base for such an analysis. Table 5 gives an outline for a research agenda including all these aspects. This research agenda can be divided into three sub-programmes which are obviously closely related, but could be treated somewhat separately.

[20] www.sustainability-geoscope.net

Table 5: Summary of research scope

Research questions	Policy relevance	Theoretical challenges	Modelling tasks	Data needs
Food demand: **What are the major driving forces of dietary changes?**	Food security, Public health, Food safety	Endogenous preference change, "Personal and social capital", Psychology/ Sociology/ Economics Interface	Interdependent utility functions, Scenario development, Learning effects, Substitutability, Lifestyle diffusion	Value surveys at different scales, Sociological clustering
Food trade: **How can trade make the global food system more efficient?**	WTO Doha Round, Foreign direct investment, International standards	Trade theory, Comparative advantage, Equilibrium theory, Political economy, Institutional innovation	Modularisation, Model coupling, Structural change, Uncertainty, Combining monetary with physical accounting	Social Accounting Matrices, Material Flow Analysis, Virtual water trade
Food supply: **What are the bio-physical limits to global food supply?**	Agricultural subsidies, Agricultural research, Environmental externalities	Induced technological change, Optimal taxation	Integrated modelling of economy, agriculture and biosphere, Spatial and temporal scaling, Time-step vs. optimisation	Agricultural production systems, Cost structures, Soil quality, Nutrient balances (especially nitrogen)

Dietary choices and food demand

The challenge with respect to food demand would be to explain, what the major determinants for dietary choices are, i.e. are economic factors like prices and income stronger than traditional habits or fashion? How do these choices change over time and what is the impact of health-related concerns on preference changes? The theoretical challenge would be to enhance oversimplified economic models of consumer choice by including theoretical considerations from psychology and sociology. Integrated modelling would require to capture endogenous preferences and interdependent utility functions as well as diffusion of lifestyle patterns. Research output would be highly relevant for policy-makers dealing with improvement of nutritional security, public health and food safety.

International trade and resource flows

The full environmental effects of international trade in goods and services and the related monetary and resource flows can only be fully understood, if accounting systems for monetary values and physical material flows can be more closely integrated. The prime example here is the trade with "virtual water", which is a physical resource incorporated in traded agricultural goods. The key question is, how international trade not only effects economic and social conditions in certain countries, but also how environmental conditions may improve or deteriorate due to export or import activities. The theoretical challenge would be to integrate physical environmental constraints into theories on trade and comparative advantage. In terms of tool development this would require more intensive coupling of economic models with biosphere and hydrology models, preferably in a flexible, modular fashion. This type of research would be highly relevant for trade policy design in the course of WTO negotiations and for further development of international standards in national economic accounting.

Agricultural production and environmental impacts

The impacts of agricultural production on natural conditions are strongly depending on specific local conditions. Changes in water or nutrient cycles are related to soil conditions, terrain type and local climate conditions. Hence it is necessary to link economic conditions of agricultural production to the place-specific biophysical conditions, in order to better understand their interactions. Many aspects of water and nutrient cycles, especially nitrogen cycles, are only poorly monitored and not yet well understood, but they are strongly influenced by agricultural production technologies. A theoretical challenge would be to further enhance the knowledge about how technological changes are triggered by environmental conditions for production. The key challenge with respect to modelling will be to link place-specific models of agricultural production and land use with models representing important elements of the biosphere and hydrology. The policy relevance of this research area is related to the modification of agricultural subsidies more in line with environmental policy goals, the avoidance of externalities and the design of efficient government support measures for agricultural research and technological development.

Two issues concerning temporal and spatial scaling are running across these three subprogrammes. First, integrated assessment methods could help to bridge the gap between different time scales usually applied in different disciplines. For an integrated analysis the definition of short, medium and long-term scenarios across the various disciplines involved is indispensable. Second, a unified system of spatial scaling has to be established. Grid-based research approaches have to be linked to methods relying on administrative units in a standardised way, and specific models of certain regions have to be consistently linked to more aggregated models on the global level.

A truly integrated assessment approach to the global food system as outlined in this section will comprise a wide range of specific disciplines, including psychology, nutrition science and public health, sociology, economics, agronomy, ecology, hydrology, and climate research.

4 Literature

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