The Future of Food: Scenarios for 2050

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ABSTRACT

This background article addresses key challenges of adequately feeding a population of 9 billion by 2050, while preserving the agroecosystems from which other services are also expected. One of the scenario-buildings uses the Agrimonde platform, which considers the following steps: choosing the scenarios and their underlying building principles, developing quantitative scenarios, and building complete scenarios by combining quantitative scenarios with qualitative hypotheses. These scenarios consider how food issues link to production, for example, the percentage of animal vs. vegetal calorie intake in the full diet. The first section of this article discusses *Agrimonde GO* and *Agrimonde 1* scenarios, which indicate that global economic growth and ecological intensification remain as main challenges for feeding the earth's growing population toward the mid-21st century. The second section provides the outcomes of the analysis of alternative futures for agricultural supply and demand and food security to 2050, based on research done for the International Assessment of Agricultural Science and Technology for Development. The last section of this article provides a summary analysis of food systems and functions, as well as the role of food technology that address some of the global challenges affecting the supply of more nutritious and healthy diets. It also highlights the food production by novel means (e.g., alternatives for animal products based on plant materials) and increasing the presence of potentially health-promoting compounds in food to improve human and animal health. Finally, this article proposes priority areas that should be included in further agri-food research.

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Abbreviations: AKST, Agricultural Knowledge Science and Technology; FAO, Food and Agriculture Organization of the United Nations; GDP, gross domestic product; IAASTD, International Assessment of Agricultural Science and Technology for Development; IMPACT, International Model for Policy Analysis of Agricultural Commodities and Trade; MEA, Millennium Ecosystem Assessment; OECD, Organisation for Economic Co-operation and Development.

Providing humankind with enough food has been a challenge throughout the ages. This topic remains of importance, but food production has changed considerably in the last 50 to 100 yr. Food security and quality improved tremendously in the industrialized world, but increasing obesity suggests humankind's difficulty in handling overweight. The impact of food production on the environment has also become problematic. However, on a global scale, food security and quality are not yet realized, and even though the situation has changed in the past century, we are still faced with tremendous challenges that require new food options to provide nutritious and healthy diets to overcome malnutrition. The following options may assist in this endeavor:

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1. Increasing the content of micronutrients in the edible parts of crops through plant breeding (i.e., biofortification).
2. Producing protein-rich products by novel means, based on plant materials, as alternatives for animal products.
3. Eliminating potentially toxic compounds in staple foods.
4. Reducing constitutive or microbial toxins in selected staples that impact food quality, safety, and human health.
5. Evaluating biofortification strategies in the context of other approaches, such as diversification of diet, to improve the diets of nutritionally disadvantaged people.

World food prices rose dramatically between 2000 and 2008 before beginning to decline later in 2008. A major cause of soaring food prices was the rapid growth in demand for biofuels, which has diverted land from food production. Other factors, many of them long term, have also contributed to the current food supply-and-demand situation. Rapid economic growth and urbanization, particularly in Asia, have driven rapid demand for meat and for maize (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.] for livestock feed. Improved economic growth in Africa has increased the demand for staples such as rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.). Meanwhile, agricultural productivity growth, especially in developing countries, continues to drop and the decline of global food stocks in the last 5 yr has led to very tense cereal markets, worldwide. Growing water scarcity and climate change are also increasingly affecting food production and prices. Poor and food-insecure households are among the hardest hit by rising food prices and, subsequently, by the global economic recession. Although households that are net sellers of food are benefiting, most poor households are net buyers of food.

This article gives some scenarios of the future of food toward 2050. Two scenarios are built on Agrimonde foresight models, which address challenges for feeding the world (Agrimonde, 2009). The third scenario ensues from analyzing alternative futures for agricultural supply and demand, and food security. This article ends summarizing food systems and functions, and how food technology addresses some of these global challenges affecting the supply of more nutritious and healthy diets.

AGRICULTURE AND FOOD IN THE WORLD OF 2050: SCENARIOS AND CHALLENGES FOR A SUSTAINABLE DEVELOPMENT

Agrimonde was established as a collective instrument—led by the French Initiative for International Agricultural Research on behalf of the Institut National de la Recherche Agronomique and the Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)—for analyzing global food and agricultural issues under the scenario of feeding 9 billion people by 2050, while preserving agro-ecosystems from which other services and products are expected (including climate change, carbon storage, biodiversity, bio-energy, or bio-materials) (Chaumet et al., 2009). The variables considered for the analysis are multifarious, including geopolitical, social, cultural, sanitary, economical, agronomical, ecological, or technological, to cite just a few (Agrimonde, 2009). The global scale at which such issues are raised does not preclude reflections at the regional level, which are necessary to account for the diversity of the world's food and agriculture, and their interactions, especially through trade that contains other key variables.

The classical scenario method is based on a first step of exhaustive recording of all kinds of variables likely to impact on the future of the system studied, within the timeline chosen for a future's study (De Jouvenel, 2000). The classical method of scenario-building would not be suitable considering the number and the diversity of variables, as well as the importance of articulating the regional and global contexts. This exercise would have been both unwieldy and largely indecipherable by combining the hypotheses on all the key variables for the future of a given agro-ecosystem investigated at both regional and global levels. The method was, therefore, adapted by building a tool based essentially on the complementarity of quantitative and qualitative analyses. The quantitative module *Agribiom* was developed by B. Dorin and T. Le Cotty (CIRAD, Montpellier, France) by formulating quantitative hypotheses at the regional level, on a limited number of variables, thereby reducing the complexity, while affording an entry point for in-depth qualitative reflection on all the dimensions of the agro-ecosystem. This scenario-building considers the following main steps: (i) choosing scenarios and their underlying building principles, (ii) developing quantitative scenarios, and (iii) building complete scenarios by combining quantitative scenarios with qualitative hypotheses.

Choice and Principles of the Scenarios

For the 2006–2008 phase, the *Agrimonde* project chose the Millennium Ecosystem Assessment (MEA) scenarios, in particular Global Orchestration, to analyze it from the angle of food and agricultural systems, and to construct a single new scenario that departed from those of the MEA scenarios (Agrimonde, 2008). The MEA scenarios, which are references in international debates, were originally built to study the future of ecosystems. Hence, they are not necessarily the most relevant for considering the future of food and agricultural systems. It is nevertheless

interesting to compare the two types of approaches: one regarding ecosystems and the other regarding the human activities that have the strongest impact on ecosystems.

As a baseline comparison, *Agrimonde* chose to reconstruct the MEA scenario Global Orchestration, which is a trend scenario on food consumption, but with different underlying societal priorities. Global Orchestration is the MEA scenario with the largest reduction of poverty and malnutrition. It is based on both the liberalization of trade and on major technical advances in terms of agricultural yields. The priority given to economic development in this scenario, nevertheless, results in an exclusively reactive management of ecosystems and environmental problems. This scenario was called *Agrimonde GO* because it was reconstructed on the basis of the quantification method adopted in *Agrimonde*, and because the population hypotheses chosen for this scenario are not precisely those used in the MEA.

The MEA scenarios are exploratory because they explore the consequences of changing trends by starting with the present situation. Some experts, including those involved in the MEA, indicated the need for a desirable scenario on the future of ecosystems. As a result, a new scenario (*Agrimonde 1*) was developed. The hypothesis of *Agrimonde 1* uses as reference points a combination of the MEA scenario and the one proposed by Griffon (2006), who describes agriculture considering all characteristics of sustainability and the potential and conditions of a "doubly green revolution" (Conway, 1997). This type of agriculture would be characterized by agricultural production technologies that both preserve ecosystems and allow for development through agriculture in countries lacking capital, where the implementation of production systems requiring intensive use of equipment, pesticides, and fertilizers is limited. The same "population pressure" hypotheses are used for comparing the *Agrimonde 1* scenario to the *Agrimonde GO* scenario.

Agrimonde 1 can be regarded as a normative forecasting scenario because it aims to explore the meaning and conditions of existence of a scenario on the development of a sustainable food and agricultural system. The idea was to better understand the meaning of such development, with the dilemmas and the main challenges that this type of scenario entail, and through the changes and discontinuities that it implies.

The World in 2050, as described in *Agrimonde 1*, is based above all on sustainable food conditions, allowing for the reduction of inequalities in food and health through a drastic reduction of both undernourishment and excessive food intake. The World in 2050 will need to implement a set of actions to intensify productive systems and to increase production in most regions. These actions will meet the following objectives: satisfying the growing demand, allowing for the development of income from agriculture in rural areas of the Global South, and developing environmentally friendly agricultural practices. These two scenarios are constructed differently; while *Agrimonde GO* is essentially a trend scenario starting from the current situation, *Agrimonde 1* is built on the basis of sustainability objectives that are supposed to be met by 2050, and explores the trajectories that would enable them to be attained.

Two underlying principles constitute the *Agrimonde 1* and *Agrimonde GO* scenarios:

1. Assessing the capacity for each large region of the world to satisfy its food needs in 2050, thereby implying that interregional trade would be considered only after evaluating the extent to which agricultural production in each region covered local needs.
2. Identifying the effects of future population trends independently of the large international migratory flows, so that the implications of expected population explosions could be examined fully with regard to each region's capacity to feed its own population.

In its present form, *Agrimonde 1* as a tool limits the construction of scenarios for the world's food and agriculture in 2050 in several ways. First, there are no precise and complete quantitative estimations for the consequences of climate change on the world's agriculture. Consequently climatic phenomena (greater variability, alterations in rainfall, rising temperatures, or melting of certain areas) have not been taken into account. Nonetheless, the panel of experts, inspired by the scenarios from the Intergovernmental Panel on Climate Change, modulated their hypotheses in relation to the surface areas under crops and to the possible yields in 2050 in the different regions. Second, even if the notion of pressure on natural resources is dominant in the analysis in various respects (e.g., deforestation resulting from the extension of farmlands, water shortages induced by climatic and demographic changes, or deterioration of the quality of the soil and water caused by farming practices), the quantitative module does not integrate indicators of the consumption of natural resources, such as quantities of water or energy consumed.

Finally, *Agrimonde 1* is based on the hypothesis that agricultural development is a driving force of global economic development and poverty alleviation (World Bank, 2008). This tool nevertheless enables us to verify whether the supposed regional increases in agricultural production effectively contributes to sufficient economic development, especially to avoid mass migration.

Food Consumption in 2050

In the *Agrimonde* scenarios, as in the MEA scenarios, "food availability" serves as an approximation of food consumption. It is calculated as the balance between the calorie equivalent of quantities of available foodstuffs (production + imports − exports ± stock variations) to feed the human population in a region (i.e., excluding animal

feed, non–food uses, seeds, and postharvest losses), and the number of inhabitants of that region. It reflects the quantity of calories available to consumers, at home and through other channels, and includes calories that will be lost between the purchase of the products and their ingestion. It should not be confused with the quantity of calories actually ingested, which is difficult to estimate. In terms of ingestion, the net energy needs of a human being are around 2000 to 3000 kcal daily, depending on sex, height, weight, and intensity of physical activity.

Food consumption trends are very different between *Agrimonde GO* and *Agrimonde 1* (Fig. 1). *Agrimonde GO* uses the hypotheses from the MEA Global Orchestration scenario in which economic growth largely explains consumption levels. Total availabilities at regional and world levels are given in the MEA report, but they were not split by product. Precise extrapolations were made in the *Agrimonde* report to quantify the food consumption hypotheses of the *Agrimonde GO* scenario. *Agrimonde GO* can qualify as a trend scenario in terms of the evolution of the total food calorie consumption, where economic growth boosts consumption in all regions to reach a mean global availability of 3590 kcal per capita daily and substantially reducing undernourishment.

The *Agrimonde 1* scenario is clearly distinguished from the *Agrimonde GO* trend scenario. The income–food consumption nexus is not the main determinant because of great concerns for health, equity, and the environment. The hypothesis of food availability that the *Agrimonde* expert panel selected for 2050 is 3000 kcal per capita daily in all regions, notwithstanding certain regional particularities visible in the breakdown in terms of animal calorie sources (monogastric, ruminants, and halieutic). This set of hypotheses is in sharp contrast with the trends observed between 1961 and the beginning of the 21st century. It corresponds to a slow growth of food availability per capita in most regions up to 2050, except in sub-Saharan Africa, where the per capita food availability will increase by 20% in 50 yr, and the Organisation for Economic Co-operation and Development (OECD)–1990 region, where it will decrease by one-fourth (Fig. 1). The 3000 kcal are broken into 2500 kcal of plant products and 500 kcal of animal products. Within animal products, the proportion due to monogastrics is increasing in all regions, whereas the proportion due to ruminants is declining despite high levels in OECD-1990 countries, the former Soviet Union and Latin America, and an increase in sub-Saharan Africa. Calories of aquatic origin increased their share in varying proportions, which are linked to regional productive possibilities. Although the oceans are a considerable source of food production, fishing will face structural limits related to several factors (overfishing, artificialization of the littoral, pollution, accelerated erosion of the biodiversity). It is assumed that marine aquaculture can increase at a faster pace than it has over the past 40 yr, but at a different pace depending on the region. In *Agrimonde 1*, the pace of the development of marine aquaculture is high in Asia, OECD-1990, and Latin America, and moderate in the other regions. Relative stability in per capita availability of calories from freshwater fish is expected, as the existing (and increasing) tension over freshwater availability prevents any increase in freshwater fishing. Trends in relation to population increases in each region were thereafter calculated.

The set of hypotheses on food consumption assumes that people's diets will depart from current tendencies as they take into account the objectives of sustainable development, which will ensue from the mounting pressure on resources and public health problems associated with human diets. It is a very strong set of hypotheses, as it implies that consumers, producers, and public policymakers will take into account the global and local impacts of modes of food production and consumption on health and the environment. This set of hypotheses corresponds to four challenges:

1. *The wide gap between the observed availability and the necessary availability for food security.* The actual mean daily availability in 2000 was close to 4000 kcal per capita daily in the OECD-1990 zone and just under 4500 kcal per capita daily in the United States, whereas the Food and Agriculture Organization (FAO) of the United Nations deems satisfactory a mean daily per capita availability of 3000 kcal to guarantee that each individual has sufficient healthy food (FAO, 2002). These gaps can be explained by the distribution of diets within the population, by the fact that in rich countries the 3000-kcal threshold may be simply exceeded, and by a great proportion of loss between the available food and actual consumption, linked to consumption habits.
2. *The importance of equity in a sustainable development scenario.* Instead of using the assumption suggested by Collomb (1999) that each region attains at least 3000-kcal per capita daily threshold, with some countries exceeding that level, *Agrimonde* chose to test a stronger hypothesis that there will be a convergence of average availabilities of food worldwide.
3. *The food/health nexus.* A daily per capita availability of 3000 kcal may have positive consequences in terms of public health by (i) maintaining the proportion of undernourished people at a relatively low level, thus reducing the risks of malnutrition in developing countries; and (ii) limiting overconsumption, a source of nontransmissible food-related diseases such as obesity. Public actions aimed at changing food-related behaviors are a response to the current increase in obesity.
4. *The relationship between diet and the pressure on natural resources.* The aim of adequately feeding 9 billion

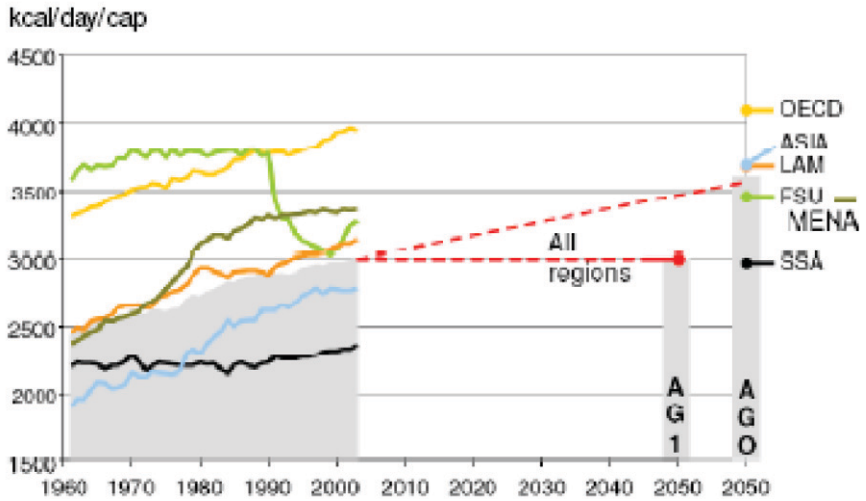

Figure 1. Mean regional food availability (daily kcal per capita) trends in *Agrimonde* Global Orchestration (AGO) and *Agrimonde* 1 (AG1) scenarios. The data used for this figure (1961–2003) ensued by reprocessing data from the Food and Agriculture Organization (FAO) of the United Nations. FSU: former Soviet Union States, LAM: Latin America, OECD: Organisation for Economic Co-operation and Development (or so-called developed world), MENA: Middle East and North Africa, SSA: sub-Saharan Africa.

people in 2050 implies that, irrespective of the production methods, there will be considerable pressure on natural resources that will increase along with the growing proportion of animal products in people's diets. The production of animal calories requires a substantial volume of plant calories, water, and energy. In addition, breeding ruminants generates greenhouse gases directly or indirectly (e.g., through animal fodder, processing, and transport). This last component is increasing with the intensification of production. Caution is nevertheless required, considering the environmental impact of animal production. One can also consider that there is an advantage in producing animals that optimize the use of plant resources (e.g., grazing on pastures, which humans cannot digest). Systems have, however, been intensified over the past 40 yr, which has resulted in shrinking pastures and concentrates, especially for grains. Producing ruminants still has the advantage of using land that is often unfit for crops (e.g., high altitudes, slopes, or semiarid areas), and of storing carbon on such lands. Furthermore, ruminants also have various uses because they represent a form of capital for their owner, provide organic fertilizer, are often used as draft animals, and are sources of food and regular income for populations often among the poorest in the world.

The World in 2050 in the Agrimonde *Scenarios*

The analysis of scenarios, in terms of coherence and action levels, and their comparison, enabled the identification of certain qualitative hypotheses in the *Agrimonde 1* scenario. On this basis, the factors that had not yet been considered in the analysis, but that were likely to have a decisive impact on the world's food and agriculture during the period leading up to 2050, were sought. These factors have been grouped into seven main themes: (i) the global context, (ii) international regulations, (iii) the dynamics of agricultural production, (iv) the dynamics of biomass consumption, (v) the actors' strategies, (vi) knowledge and technologies in the field of food and agriculture, and (vii) sustainable development. A complete scenario was built by developing hypotheses on these different dimensions, with a concern for the overall coherence and plausibility of the scenarios. A possible account of the *Agrimonde 1* scenario is proposed here, as well as that of *Agrimonde GO*, which corresponds to the MEA experts' forecasts (Carpenter et al., 2005). This article will focus on Points vi and vii.

Agrimonde GO: *Feeding the World by Making Global Economic Growth a Priority*

The global availability of calories for consumption as food, per day and per capita, will increase by 818 calories between 2000 and 2050. The steepest increases will be in Asia, sub-Saharan Africa, and Latin America, and the number of children suffering from malnutrition in developing countries will decrease by a factor of 2.5 during the first half of the century. This trend, stimulated by the rapid economic growth and intense urbanization, will be accompanied by a richer protein content of diets as people consume more meat and fish. It will result in the growth of obesity in many regions (Asia, Africa), where new nutrition policies need to be implemented.

Technological development will allow for more intensive farming, as well as for an extensive use of fertilizers and genetically modified crops. The vast majority of farms, both small and large, will become highly mechanized and industrial. Local know-how will often

be replaced by standardized industrial methods and the variety of agricultural species will be reduced. Multinational firms are a predominant feature of this scenario, as they will increase their share of plant and animal production, primarily through the development of new genetic strains. Nevertheless, it needs to increase the cultivated area by 18%, with yields close to 33,000 kcal ha^{-1} daily.

Agrimonde 1: *Feeding the World by Preserving Ecosystems*

In 2050, diets in the various regions of the world would converge regarding calorie intake. On average about 3000 kcal per capita daily would be available worldwide. Cultural particularities would nevertheless maintain some diversity in the distribution of the various food sources. Increasing income would not lead to a convergence of diets toward western diets. Even though in certain regions, especially in sub-Saharan Africa, food consumption trends are initially based on economic development, they also stem from behavioral changes in most regions. For instance, in a region like OECD-1990, the mean calorie consumption has declined from 4000 to 3000 kcal per capita daily. This steep downward trend is the result of less wastage by users or in catering systems, and more effective nutrition policies. The maintenance of diversity of diets also helps to solve problems of deficiencies in micronutrients, primarily through the consumption of fruit and vegetables. The fast growth of the proportion of raw products compared with processed products, recorded at the beginning of the century, has leveled off. This is a symptom of the diversification of food systems. It also stems from regulations that have placed strong constraints on agri-food companies' information and communication on nutrition in the rich countries, encouraging them to limit the degree of product processing, while continuing to sell products that are innovative, in terms of practicality and variety.

From 2000 to 2050, the agri-industrial model, initially clearly dominant, merges increasingly with the local food and agricultural systems based on short circuits and on the diversity of small and medium-sized farms and processing enterprises, especially in the developing world. The tendency toward standardization, internationalization, and concentration around a limited number of multinational firms declines. This change is facilitated by national and regional strategies to ensure food security, and by the considerable impact of corporate social responsibility (CSR) on large firms' strategies. The agri-food sector is strongly affected by CSR as consumers in the rich countries prove to be more and more concerned about food issues, due to the spread of the sustainable food concept and following the "hunger riots." They pressure agri-food firms, often via nongovernmental and consumer organizations, to take on their particular role in economic development and the reduction of malnutrition, as well as in the struggle against obesity. According to this scenario, the increase of cropping area needed is almost 39% more than the current state, with yields varying from 20,000 to 30,000 kcal ha^{-1} daily. In this case, there is a huge need for new models of agricultural activities facing new ways of combining the ecological and productive functions of agroecosystems in the same area corresponding to a model that can be qualified as "integrationist." It is based on the combination of different types of productive systems in a given territory, adapted to the local ecosystems in such a way as to maintain it in the form of a mosaic of ecosystems producing a diversity of services (e.g., purifying and regulating water resources, soil conservation, maintenance of landscape structures and biodiversity, or carbon fixation). This model involves different types of farming (such as livestock, forestry, or crops) in the same territory, on the same farm or on different farms, overlapping to differing degrees (see the mode of ecological intensification in the *Agrimonde 1* scenario for the North Africa–Middle East, sub-Saharan Africa, Latin America, and Asia regions).

Ecological Intensification, Performance Criteria, and (Ir)Reversibility of Choices

Today the concept of ecological intensification essentially refers to tailoring technical options, rather than prescribing a set of processes that can be applied uniformly everywhere. These so-called technical options encompass social, economic, spatial, and political options that are not incidental and have probably not been sufficiently explored. However, enough is known about the options that have accompanied the process of rationalization (also known as "modernization") of North American and European agriculture, so that they enable us to clarify the conditions required for a particular option.

In the *Agrimonde 1* scenario, the agricultural performance criteria are no longer limited to tech-economic indicators. They encompass a range of indicators at the territorial level that pertain to the efficiency of agricultural practices regarding water quality, biodiversity, and soil quality conservation, as much as on commercialized production. In this scheme, the different types of productive systems described above are no longer exclusive, but they are complementary to each other by allowing for efficient management of the diversity of the ecosystems involved. The *Agrimonde 1* scenario is a fine illustration of such complementarity. For instance, in Latin America forests are devoted no longer to clearing for land use or protection, but to intermediate forms corresponding to various agroforestry models. In Asia humid areas are not all drained, but rather they are valued as a source of grazing land in dry seasons or for combined agricultural and aquaculture projects. In North Africa–Middle East and in sub-Saharan Africa, rangelands with low forage productivity become key elements in grazing routes that use a diversity of environments and biological corridors, enabling the fauna and

flora to circulate. The same applies to hedges, small woods, and orchards, habitats for many crop auxiliaries and coarse substances that preserve the soil and low-lying vegetation from the effects of wind and rain. In the *Agrimonde 1* scenario, farms with a low level of efficiency, in terms of exclusively tech-economic criteria, play an important role in this respect in 2050. They make the multifunctionality of agriculture fully meaningful; that is, not only a farming activity that provides goods and services apart from agricultural goods, whether for food or not, but also one of the activities practiced in a territory by some of the households living there. In this sense it is both the territory and the households that are multifunctional, as agriculture as such represents only one of these functions.

The *Agrimonde 1* scenario integrates a change of viewpoint on the multifunctionality of agriculture, assessed as essential by both the recommendations of the 2008 *International Assessment of Agricultural Knowledge, Science and Technology for Development* (IAASTD, 2008) and by the *World Development Report 2008* (World Bank, 2008) on agricultural issues. One of the first tasks to make it meaningful would consist of producing performance criteria to evaluate the accomplishment of the different functions, not merely to remunerate them, but to frame them politically and to administer them. It would become evident that in such a scheme the different types of agriculture complement one another rather than having to fit into a single model (e.g., from commercial specialized to family multipurpose farming).

In both scenarios, the question remains as to the real capacity for emerging new technology options, which are affected also by other factors including social, economic, and local development issues. It could prove difficult to break away from past choices that are embedded in current technical solutions (e.g., mechanization, fertilizer and pesticide use, or genetic engineering) as well as in cognitive systems (such as knowledge and know-how, representations of nature, pollution, or landscapes) and in the values of the main actors involved. Are we not trapped in a technical rationalization? It is a sort of lock-in that other sectors have also experienced—except we cannot do without agriculture!

FOOD SUPPLY AND DEMAND FOR FOOD SECURITY

This section examines the new realities of the global food system, presenting the outcomes of the analysis of alternative futures for agricultural supply and demand and food security to 2050, based on research done for the IAASTD (Rosegrant et al., 2009).

Drivers that Influence the Future of Food Supply and Demand and Food Security

Drivers that influence the future of food supply and demand and food security include any natural or human-induced factors that directly or indirectly influence the future of agriculture. Indirect drivers include demographic, economic, sociopolitical, scientific and technological, cultural and religious, and biogeophysical change. Important direct drivers include changes in food consumption patterns, natural resource management, land use, climate, energy, and labor. The key quantitative drivers in this scenario assessment are summarized below.

Baseline Quantitative Modeling Assumptions

The baseline case forecasts a world developing out to 2050 as it does today, without deliberate interventions requiring new or intensified policies. The key assumptions of the reference case include:

1. *Population*. The baseline (as well as alternative policy experiments) uses the United Nations medium variant projections (United Nations, 2005), with the global population increasing from slightly more than 6.1 billion in 2000 to >8.2 billion in 2050. Population growth drives changes in food demand.
2. *Overall economic growth*. Economic growth assumptions are based on the TechnoGarden scenario of the MEA (Carpenter et al., 2005). Incomes are expressed as MER-based values. The TechnoGarden scenario assumptions are near the midrange growth scenarios in the literature for the world as a whole and most regions. In some regions, such as sub-Saharan Africa, the scenario is relatively optimistic.
3. *Agricultural productivity*. Agricultural productivity values are based on the MEA (TechnoGarden scenario) and the recent FAO interim report projections to 2030/2050 (FAO, 2006). The MEA assumptions have been adjusted from the TechnoGarden scenario assumptions to conform to FAO projections of total production and per capita consumption in meats and cereals, and to our own expert assessment. The main recent technological change developments, with continued slowing of growth overall, have been taken into account. Growth in numbers and slaughtered carcass weight of livestock has been similarly adjusted.
4. *Nonagricultural productivity*. In the reference case, in general, productivity growth is projected to be lower in nonagricultural than in agricultural sectors. The nonagricultural gross domestic product (GDP) growth rates are based on the MEA TechnoGarden scenario, but with adjustments to align with World Bank medium-term projections. While the relatively higher productivity in agriculture largely reflects the declining trends in agricultural terms of trade, this is not translated into higher output growth in agricultural sectors relative to nonagricultural sectors. This broadly confirms Engel's Law that the budget share of food falls with increasing income.

5. Disparities in growth rates among developing countries are projected to remain high, while more developed regions will see more stable growth out to 2050. Developed regions will see relatively low and stable to declining growth rates between 1 and 4% yr^{-1}. Latin America is also expected to experience stable growth rates, though slightly higher than for developed regions—between 3.5 and 4.5% yr^{-1}. The GDP growth in East and Southeast Asia is expected to be stable, with relatively high rates of 4 to 7% yr^{-1}. In particular, China's economy is projected to slow from the 10% growth in recent years to a more stable rate of 5.6% yr^{-1}. On the other hand, growth in South Asia—following strong reforms and initiatives focusing on macroeconomic stabilization and market reforms—is expected to lead to improved income growth in that subregion of 6.5% yr^{-1}. The Middle East and North Africa is expected to see GDP growth rates averaging 4% yr^{-1}. Growth in sub-Saharan Africa has been low in the recent past, but there is room for recovery, which is projected to lead to modest to strong growth just under 4% yr^{-1}. Growth in Central and Western Africa is expected within the 5 to 6% range. Growth in East and Southern Africa is expected at <4% out to 2025, followed by more rapid growth of 6 to 9% by 2050.
6. *Trade policies.* Today's trade conditions are presumed to continue out to 2050. No trade liberalization or reduction in sectoral protection is assumed for the reference scenario.
7. *Climate change.* Climate change is both driving different outcomes of key variables of the baseline (such as crop productivity and water availability) and is an outcome of the agricultural projections of the reference run, due to land-use changes and agricultural emissions, mainly from the livestock sector. Medium energy outcomes are assumed in the baseline. The B2 scenario was used for the analysis. From the available B2 scenario, the ensemble mean of the results of the HadCM3 model for the B2 scenario was used. The pattern scaling method applied was that of the Climate Research Unit, University of East Anglia. The "SRES B2 HadCM3" climate scenario is a transient scenario depicting gradually evolving global climate from 2000 through 2100.
8. *Biofuels.* The baseline, based on actual national biofuel plans, assumes continued expansion in production of biofuels through 2025, although the rate of expansion declines after 2010 for the early rapid growth countries such as the United States and Brazil. Under this scenario, significant increases in biofuel feedstock demand occur in many countries for commodities such as maize, wheat, cassava (*Manihot esculenta* Cranz), sugar, and oil seeds. By 2020, the United States is projected to put 130 million t of maize into biofuel production; European countries will use 10.7 million t of wheat and 14.5 million t of oil seeds; and Brazil will use 9 million t of sugar equivalent. We hold the volume of biofuel feedstock demand constant starting in 2025 to represent relaxed demand for food-based feedstock crops created by the rise of new technologies that convert nonfood grasses and forest products.

Models Used in the Study

Two types of models were used for the study: partial agricultural equilibrium models and computable general equilibrium (CGE) models. Both types were used for analyses at the national (India and China) and regional or global levels. The partial equilibrium agricultural sector model—International Model for Policy Analysis of Agricultural Commodities and Trade, or IMPACT (Rosegrant et al., 2002)—provided insights into long-term changes in food demand and supply at a regional level, taking into account changes in trade patterns using macroeconomic assumptions as an exogenous input.

The IMPACT model was developed at the beginning of the 1990s, on the realization that there was a lack of long-term vision and consensus among policymakers and researchers about the actions that are necessary to feed the world in the future, reduce poverty, and protect the natural resource base. This model has been used in several important research publications, which examine the linkage between the production of key food commodities and food demand and security at the national level. The most comprehensive set of results for IMPACT are published in the book *Global Food Projections to 2020* (Rosegrant et al., 2001). These projections are presented with details on the demand system and other underlying data used in the projections work, and cover both global and regionally focused projections. This IMPACT model was further expanded through inclusion of a water simulation model, as water was perceived as one of the major constraints to future food production and human well-being.

The Global Trade and Environmental Model (GTEM)—A CGE model, developed by the Australian Bureau of Agricultural and Resources Economics (Ahammad and Mi, 2005), was used to validate the GDP and population input data to achieve cross-sectoral consistency and to implement trade analysis. The GTEM is a multiregion, multisector, dynamic, general equilibrium model of the global economy, which addresses policy issues with global dimensions and issues where the interactions between sectors and between economies are significant. This includes international climate change policy, international trade and investment liberalization, and trends in global energy markets. In addition, the IAASTD analyses used the integrated assessment model IMAGE 2.4 (Eickhout et al., 2006) for

climate change impacts and land use, and the livestock spatial location–allocation model SLAM (Thornton et al., 2002, 2006) for a more detailed livestock assessment.

Baseline Results

Food Supply and Demand

The baseline was a 3-yr average centered on 2000 for all input parameters and assumptions for driving forces. Following this baseline, global cereal production increases 0.9% yr^{-1} for the 2000–2050 period. The year 2000 reflects a 3-yr moving average for 1999 to 2001, and 2050 reflects a 3-yr moving average of 2048 to 2050 unless noted otherwise. Growth of food demand for cereals slows during the 2000–2025 period and again from 2025 to 2050, from 1.4 to 0.4% yr^{-1}. The demand for meat products (beef, sheep, goat, pork, and poultry) grows more rapidly but also slows somewhat after 2025, from 1.8 to 1% annually.

Changes in cereal and meat consumption per capita vary significantly among regions (Fig. 2 and 3). Over the projections period, per capita demand for cereals as food is expected to decline by 27 kg in East Asia and the Pacific and by 11 kg in Latin America and the Caribbean. On the other hand, demand is projected to increase by 21 kg in sub-Saharan Africa. Per capita meat demand is projected to more than double in South Asia and sub-Saharan Africa, almost double in East Asia and Pacific, and increase by 50% in the Middle East and North Africa. In the developed countries, only a minor 4% increase is projected, given that demand is already very high.

Total cereal demand is projected to grow by 1048 million metric t, or by 56%: 45% of this increase is expected for maize; 26% for wheat; 8% for rice; and the remainder for millet [*Pennisetum glaucum* (L.) R. Br.], sorghum [*Sorghum bicolor* (L.) Moench.], and other coarse grains. Rapid growth in meat and milk demand in most of the developing world will put strong demand pressure on maize and other coarse grains as feed. Globally, cereal demand as feed increases by 430 million t for the 2000–2050 period; that is, a 41% of total cereal demand increase. Slightly more than 60% of total demand for maize will be used as animal feed, and a further 16% for biofuels.

How will expanding food demand be met? For meat in developing countries, increases in the number of animals slaughtered have accounted for 80 to 90% of production growth during the past decade. Although there will be significant improvement in animal yields, growth in numbers will continue to be the main source of production growth. In developed countries, the contribution of yield to production growth has been greater than the contribution of numbers growth for beef and pig meat, while for poultry, numbers growth has accounted for about two-thirds of production growth. In the future, carcass weight growth will contribute an increasing share of livestock production growth in developed countries, as numbers expansion is expected to slow.

For the crops sector, water scarcity is expected to increasingly constrain production, with little additional water available for agriculture due to slow supply increases and rapid shifts of water away from agriculture in key water-scarce agricultural regions in China, India, plus the Middle East and North Africa. Climate change will increase heat and drought stress in many of the current breadbaskets in China, India, and the United States, and even more so in the already stressed areas of sub-Saharan Africa. Once plants are weakened from abiotic stresses, biotic stresses tend to set in, and the incidence of pest and diseases tends to increase.

With declining availability of water and land that can be profitably cultivated, area expansion is not expected to contribute significantly to future production growth. In the baseline, cereal harvested area expands from 660 million ha in 2000 to 694 million ha in 2020 before contracting to 632 million ha by 2050. The projected slow growth in crop area places the burden to meet future cereal demand on crop yield growth.

Although yield growth will vary considerably by commodity and country, in the aggregate and in most countries it will continue to slow. The global yield growth rate for all cereals is expected to decline from 1.96% yr^{-1} in 1980–2000 to 1.01% in 2000–2050. In developed countries, annual average cereal yield growth is estimated at 0.96% yr^{-1} during 2000 to 2050, 0.9% in East Asia and the Pacific, and 1.07% in South Asia. Slightly higher yield growth is expected in the Middle East and North Africa, Latin America and the Caribbean, and sub-Saharan Africa; that is, at 1.16, 1.25, and 1.59% yr^{-1}, respectively. As can be seen in Fig. 4, area expansion is significant for projected food production growth only in sub-Saharan Africa (23%), Latin America and the Caribbean (9%), and the Middle East and North Africa (7%).

Food Trade, Prices, and Security

In the last few years, real prices of food have increased dramatically as a result of changes in biofuel/climate policies, rising energy prices, declining food stocks, and market speculation. Projections reported here show that higher food price trends are likely to stay as a result of increased pressures on land and water resources, adverse impacts from climate variability and change, and rapidly rising incomes in most of Asia. Given underinvestment in agriculture over the past few decades, and projected slow growth in investment in the baseline and poor government policies in response to rising food prices in many countries, it is unlikely that the supply response will be strong enough in the short to medium term.

Maize, soybean, rice, and wheat prices are projected to increase by 60 to 97% in the baseline (Fig. 5) and prices for

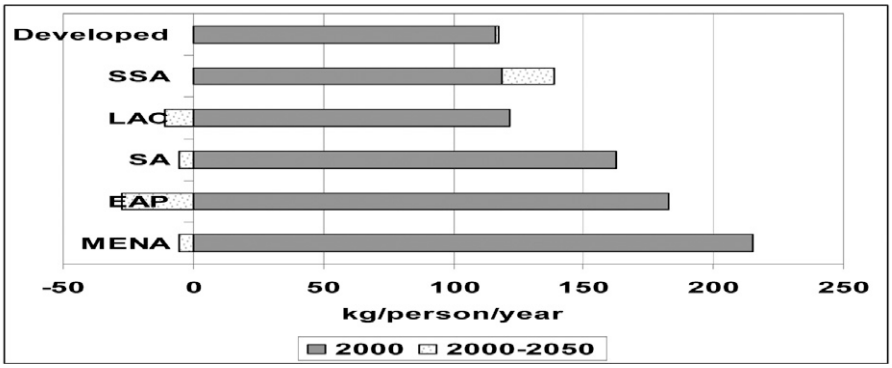

Figure 2. Per capita availability of cereals as food in 2000 and change for 2000 to 2050 by region. EAP: East Asia and the Pacific, LAC = Latin America and the Caribbean, MENA: Middle East and North Africa, SA: South Asia, SSA = sub-Saharan Africa.

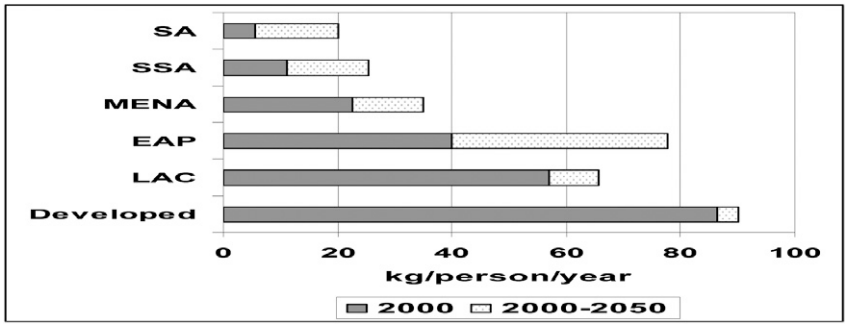

Figure 3. Per capita availability of meats in 2000 and change for 2000 to 2050 by region. EAP: East Asia and the Pacific, LAC: Latin America and the Caribbean, MENA: Middle East and North Africa, SA: South Asia, SSA: sub-Saharan Africa.

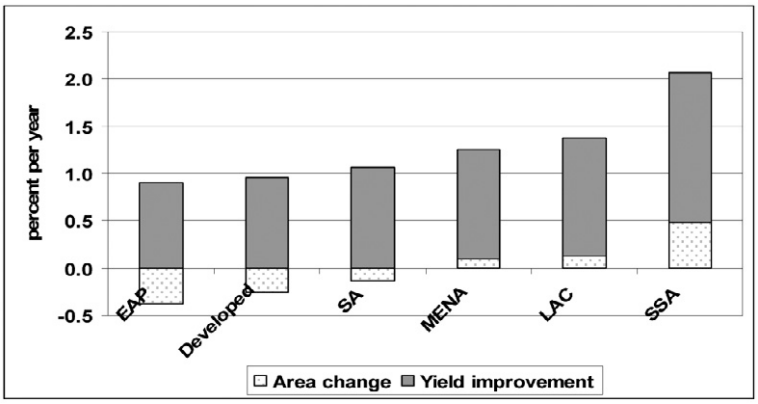

Figure 4. Sources of cereal production growth (2000–2050) by region. EAP: East Asia and the Pacific, LAC: Latin America and the Caribbean, MENA: Middle East and North Africa, SA: South Asia, SSA: sub-Saharan Africa.

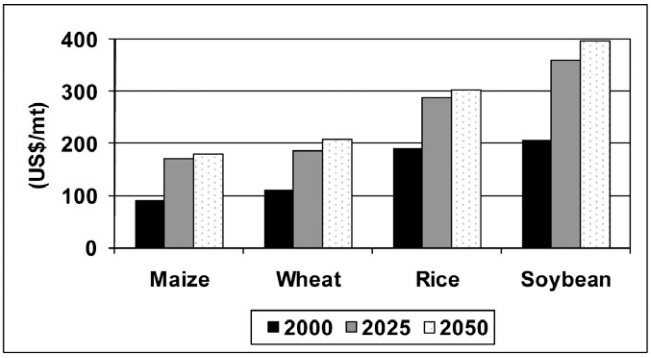

Figure 5. International food prices ($US t^{-1}) of selected grains in 2000, and projected for 2025 and 2050.

beef, pork, and poultry by 31 to 39%. Impacts of higher food prices on net food purchasers will be substantial, depressing food demand in the longer term, increasing childhood malnutrition rates, and reversing progress made in several low-income countries on nutrition and food security.

World food trade is expected to continue to increase, with cereals trade projected to increase from 257 million t in 2000 to 584 million t by 2050, and trade in meat products rising from 16 million t to 64 million t. Expanding trade will be driven by the increasing import demand from the developing world, particularly sub-Saharan Africa, East Asia and the Pacific, and South Asia, where net cereal imports will grow by >200% (Fig. 6). Sub-Saharan Africa

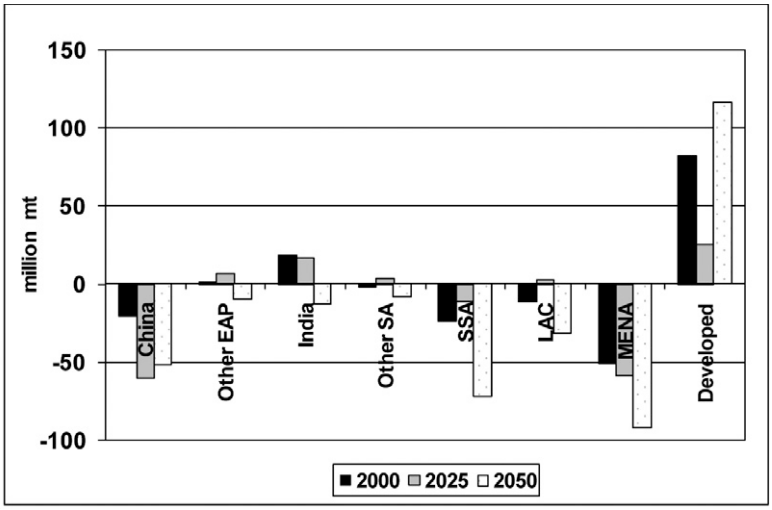

Figure 6. Net trade in cereals in 2000 and projected for 2025 and 2050. EAP: East Asia and the Pacific, LAC: Latin America and the Caribbean, MENA: Middle East and North Africa, SA: South Asia, SSA: sub-Saharan Africa.

will face the largest increase in food import bills despite the significant area and yield growth expected during the next 50 yr in the baseline. By 2050, the Middle East and North Africa is expected to account for 33% of net cereal imports, sub-Saharan Africa for 25%, and China for 19%.

With most developing countries unable to increase food production rapidly enough to meet growing demand, the major exporting countries—mostly in high-income countries and in Eastern Europe and Central Asia—will play an increasingly critical role in meeting global food consumption needs. The United States and Europe are a critical safety valve in providing relatively affordable food to developing countries. However, given the strong demand for food crops as feedstock for biofuels in the short to medium term, net cereal exports in these countries are projected to decline over the next decade before rebounding after food-crop use for biofuel feedstock is expected to decline. For example, net maize exports from the United States are expected to decline from 40 million t in 2000 to 17 million t in 2015 before rebounding and increasing to 62 million t by 2025. Net wheat exports are projected to grow to 48 million t in Russia, 41 million t in the United States, and to around 20 million t in Australia, Canada, Central Europe, and Kazakhstan. Net meat exports are expected to double in developed countries and to sharply increase in Latin America. Brazil's net meat exports are expected to increase 10-fold over the 50-yr time horizon.

The substantial increase in food prices will slow growth in calorie consumption due to both direct price impacts and reductions in real incomes for poor consumers who spend a large share of their income on food. As a result, there will be little improvement in food security for the poor in many regions. In sub-Saharan Africa, daily calorie availability is expected to stagnate up to 2025 before slowly increasing to 2762 kilocalories by 2050, compared with 3000 or more calories available, on average, in most other regions. Only South Asia (excluding India) fares worse, with only 2654 kilocalories available on average by 2050. Several regions are projected to experience declining calorie availability between 2000 and 2025 (Fig. 7).

In the reference run, malnutrition among children up to 60 mo will continue to decline slowly in most regions, but remains high by 2050, with progress far below that envisioned in the Millennium Development Goals (Fig. 8). Childhood malnutrition is projected to decline from 149 million children in 2000 to 130 million children by 2025 and 99 million children by 2050. The decline will be greatest in Latin America at 51%, followed by Central/West Asia and North Africa, and East Asia and the Pacific at 46 and 44%, respectively. Progress is slowest in sub-Saharan Africa. By 2050, an 11% increase is expected—to 33 million children in the region—despite significant income growth and rapid area and yield gains, as well as substantial progress in supporting services that influence well-being outcomes, such as female secondary education and access to clean drinking water.

ALTERNATIVE INVESTMENTS IN AGRICULTURAL KNOWLEDGE, SCIENCE AND TECHNOLOGY (AKST)

Three alternative AKST scenarios out to 2050 were analyzed to examine their implications for food supply, demand, trade, and security. The first two scenarios examine the outcome of different levels of investments in crop yield and livestock numbers growth (AKST high and AKST low). A third scenario analyzes the implications of even more aggressive growth in agricultural R&D together with advances in complementary sectors (AKST high plus). These include investments in irrigation infrastructure represented by accelerated growth in irrigated area and efficiency of irrigation water use, by accelerated growth in access to drinking water, and

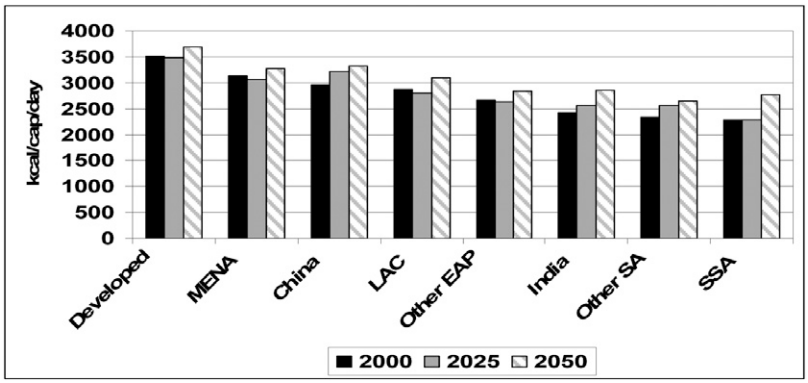

Figure 7. Calorie availability in 2000 and projected for 2025 and 2050. EAP: East Asia and the Pacific, LAC: Latin America and the Caribbean, MENA: Middle East and North Africa, SA: South Asia, SSA: sub-Saharan Africa.

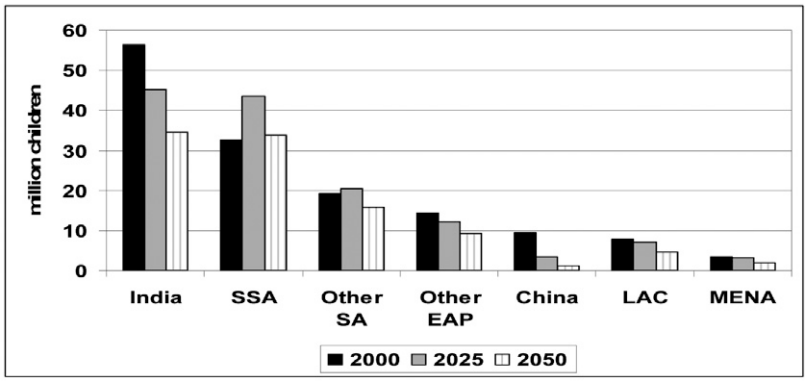

Figure 8. Number of malnourished children in 2000 and projected for 2025 and 2050, baseline. EAP: East Asia and the Pacific, LAC: Latin America and the Caribbean, MENA: Middle East and North Africa, SA: South Asia, SSA: sub-Saharan Africa.

greater investments in secondary education for females, an important indicator for human well-being (Table 1).

The AKST high variant that presumes increased investment in AKST, results in higher food production growth, which in turn reduces food prices and makes food more affordable to the poor when compared with the reference world. Under AKST high, cereal production increases by 7% and by an even stronger 17% under the AKST high plus variant. Under AKST high, rice prices decline by 46%, wheat prices by 57%, and maize prices by 65%, compared with the 2050 baseline value. On the other hand, if investments decrease faster than in the recent past, prices would rapidly increase, by 96% for rice, 174% for wheat, and 250% for maize compared with the 2050 baseline value (Fig. 9).

Despite these strong changes in AKST behavior, yield growth will continue to contribute most to future cereal production growth under both the AKST low and AKST high variants. Under AKST low, however, the contribution of area growth to overall production growth is projected to increase compared to the baseline, from 23 to 35% for sub-Saharan Africa, and from 11 to 29% in Latin America and the Caribbean. For developing countries as a whole, area change would contribute 13% to overall production growth, up from a negative 4% (contraction of area) under the baseline. This growth, coupled with rapid expansion of the livestock population under AKST high, requires expansion of grazing areas in sub-Saharan Africa and elsewhere, which could lead to further forest conversion into agricultural use.

What are the implications of more aggressive production growth on food security and trade? Under AKST high, developing countries cannot meet the rapid increases in food demand through domestic production alone. As a result, net cereal imports from developed countries would increase by 70% compared with the reference run. Net cereal imports are projected to increase from 72 to 125 million t in sub-Saharan Africa, and from 93 to 100 million t in the Middle East and North Africa, but drop by almost half in China. Under AKST low, on the other hand, high food prices lead to depressed global food markets and reduced global trade in agricultural commodities.

Sharp increases in international food prices as a result of the AKST low variant depress demand for food and reduce availability of calories. Average daily kilocalorie availability per capita declines by 850 calories in sub-Saharan Africa, pushing the region below the generally accepted minimum level of 2000 calories and thus also below the levels of the base year 2000. On the other hand, under the AKST high and AKST high plus scenarios,

Table 1. Assumptions for baseline and alternative Agricultural Knowledge, Science and Technology (AKST high, low) and infrastructure (AKST high plus) scenarios.

Parameter changes for growth rates	Base 2050	AKST high 2050	AKST low 2050	AKST high plus 2050
Gross domestic product growth	3.06% yr^{-1}	3.31% yr^{-1}	2.86% yr^{-1}	3.31% yr^{-1}
Livestock numbers growth	Base numbers growth of animals slaughtered 2000–2050 Livestock: 0.74% yr^{-1} Milk: 0.29% yr^{-1}	Increase in numbers growth by 20% Increase in animal yield by 20%	Reduction in numbers growth by 20% Reduction in animal yield by 20%	Increase in numbers growth by 30% Increase in animal yield by 30%
Food crop yield growth	Base yield growth rates 2000–2050: Cereals: 1.02% yr^{-1} Roots and tubers: 0.35% yr^{-1} Soybean: 0.36% yr^{-1} Vegetables: 0.80% yr^{-1} Fruits: 0.82% % yr^{-1}	Increase growth by 40%	Reduce growth by 40%	Increase growth by 60%
Irrigated area growth	0.06			Increase by 25%
Rainfed area growth	0.18			Decrease by 15%
Basin efficiency				Increase by 0.15 by 2050
Access to water				Increase annual rate of improvement by 50% relative to baseline level
Female secondary education				Increase overall improvement by 50% relative to 2050 baseline level

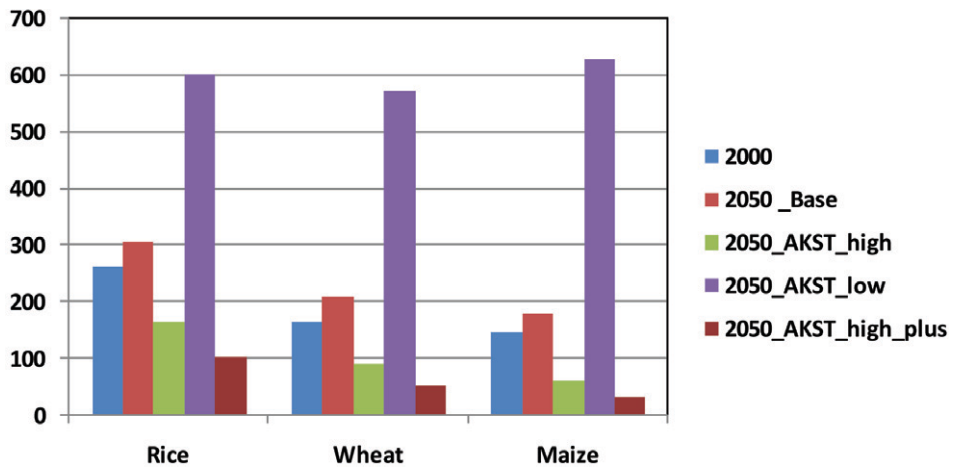

Figure 9. Cereal prices (US$ t^{-1}) in 2050 per alternative Agricultural Knowledge, Science and Technology (AKST) scenarios.

calorie availability increases in all regions compared with 2000 and baseline levels.

Calorie availability—together with changes in complementary service sectors, including female secondary education, female-to-male life expectancy at birth, and access to clean drinking water—can help explain changes in childhood malnutrition levels (Rosegrant et al., 2001). Under the AKST high and AKST high plus variants, the number of malnourished children in developing countries is projected to decline by 24 and 56%, respectively, from 104 million children under the baseline (Fig. 10). On the other hand, if investments slow more rapidly and supporting services degrade rapidly, then absolute childhood malnutrition levels could return to close to 2000 malnutrition levels at 137 million children in 2050 under the AKST low variation.

What are the implications for investment under these alternative policy variants? Investment requirements for developing countries in the baseline run for key sectors, including public agricultural research, irrigation, rural roads, education, and access to clean water, are calculated at nearly US$32 billion per year at 2008 prices. As Fig. 11 shows, the much better outcomes in developing country food security obtained under the AKST high plus variant can be achieved at estimated annual investment increases in the five key sectors of US$20 billion and are within reach if the political will and resources are made available.

An Analysis of Food Production

The following trends are of importance in discussing the future of food and the role of technology. An enormous

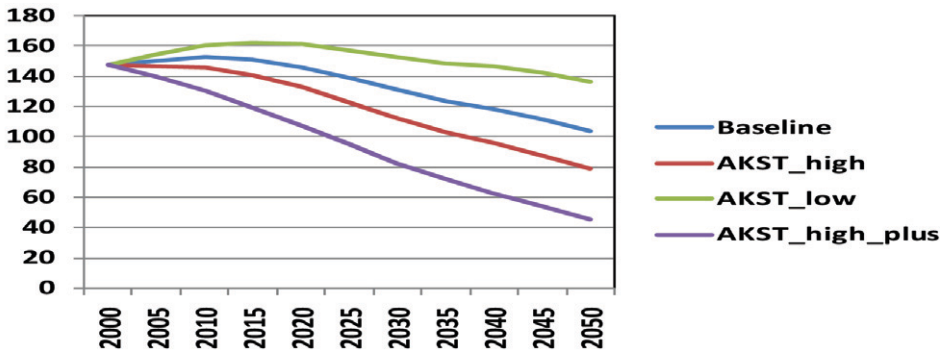

Figure 10. Number of malnourished children, developing countries, projected 2000 to 2050 for alternative Agricultural Knowledge, Science and Technology (AKST) scenarios.

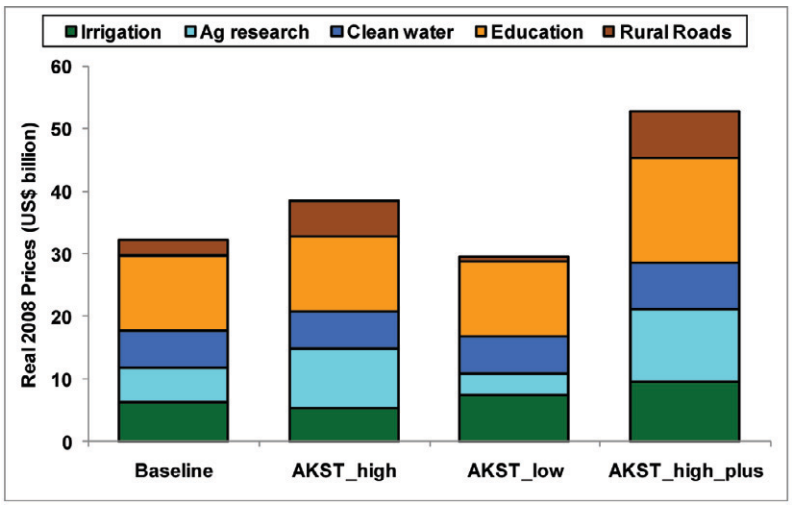

Figure 11. Annual investment requirements (2000–2050) for agriculture and complementary service sectors using alternative Agricultural Knowledge, Science and Technology (AKST) scenarios (US$ billion in 2008).

productivity increase has occurred in highly effective and efficient farming systems. This improvement has resulted in unprecedented food security in the industrialized world but seems to lead to other problems as indicated below:

1. Industrialization of farming leads to alienation of consumers toward their food.
2. Strong integration in food chains, also internationally, and consequently strong interdependencies.
3. Because of the abundant food supply (in the industrialized world), the role of the consumer has become leading and necessary. In other words, food systems are no longer supply driven but demand driven.
4. When food security is realized, food quality becomes of importance, which materializes in a strong attention for the relation between food and health.

Food Systems

Food systems can be described as comprising four sets of *activities*: producing food, processing food, packaging and distributing food, and retailing and consuming food (Ingram, 2008). The first activity of producing food is basically the production of raw materials in agriculture, horticulture, animal husbandry, and aquatic production systems. The main scientific disciplines involved are plant and animal breeding, agronomy, soil science, water management, phytopathology, and related disciplines. The main actors involved are farmers, seed companies, fertilizer and pesticides industry.

The second activity is about the processing of raw materials into food. This activity starts after harvesting and four subactivities can be distinguished (Van Boekel, 1998): stabilization, transformation, production of ingredients, and production of fabricated foods. Stabilization implies that measures are taken to prevent spoilage. The most important cause of spoilage is microbial activity, which is even dangerous as the microorganisms may be pathogenic and are a threat to human health. This threat concerns the very important aspect of food safety. Hence, many food technology activities are directed toward the prevention, or at least inhibition, of microbial growth. When microbial growth is prevented, chemical and biochemical reactions are the next cause of spoilage. This spoilage implies oxidation reactions and the so-called Maillard reaction, leading to desired changes such as browning and flavor compounds, and undesired changes such as loss of nutritive value and toxicological suspect compounds. Biochemical changes occur as a result of enzyme activity, which can lead to color,

flavor, taste, and texture problems. Transformation implies that raw materials are changed into something different, such as milk into cheese, wheat into bread, or barley into beer. Production of ingredients is self-evident: sugar can be extracted from sugar beets (*Beta vulgaris* L.) and sugarcane (*Saccharum officinarum* L.), or protein and oil from soybeans. This activity can also imply production with the help of microorganisms or enzymes. Finally, production of fabricated foods implies that foods are composed or designed from several raw materials (sauces, desserts, pastry are some examples). Disciplines involved are food science and technology and nutrition, actors involved are artisanal as well as industrial processors.

The third activity of packaging and distribution follows immediately after transformation. Some authors would actually consider packaging to be part of processing. In any case, packaging is an essential element of food technology as it protects the food against all kinds of threats from the environment. These threats include microorganisms, insects, water, oxygen, and physical damage. Likewise, packaging technology can nowadays be actively used to preserve foods by applying controlled atmosphere and modified atmosphere. This implies that the gas atmosphere influences metabolic reactions of the food as well as of the microorganisms present in a desired direction. Furthermore, packaging also functions as information carrier for the consumer, such as nutritive value, presence of possible allergens, and any other relevant information, including advertising. Disciplines involved are food science, logistics, marketing, and actors are food processors, middlemen, and retailers.

The last but not least activity is about retailing and consumption. Retailers have quite some power these days, as they are able to influence the consumer directly by determining what to offer to consumers. They seem to have appreciable governance in the food chain. Increasingly, globalizing markets are becoming important, as foods from all over the world may end up at the consumer's plate. While this is not a bad development as such, this phenomenon has several institutional implications, such as access to markets and a strong effect of rules and regulations that make it sometimes difficult for developing countries to comply with this development (Ruben et al., 2007). It also raises the question whether or not such developments are not enhancing sustainability problems. Actors involved are food processors, retailers, and consumers, and governments, to some extent, when regulation is involved.

Functions of Foods

Foods have many functions in society. First and foremost, they supply energy and nutrients that humans need to live. People need the macronutrients protein, fat, and carbohydrates. Next to that, the micronutrients vitamins and minerals are essential. Furthermore, nonnutrients such as fiber, antioxidants, and other bioactive components are needed. However, not all proteins, fats, and carbohydrates are the same. Generally, animal proteins (meat, milk, eggs) are better from a nutritional point of view than plant proteins. Fats also differ, and polyunsaturated fatty acids, and especially the ω-3/6 fatty acids, are preferred over the saturated ones. Carbohydrates that are absorbed in the gut only supply energy to the body. Dietary fibers can also be classified as complex carbohydrates that are not absorbed but are partly fermented in the colon.

Another function of food is to supply pleasure. Generally, people enjoy eating and foods deliver stimuli to the senses (eyes, tongue, nose, ears). Childhood experiences appear to be very important to what people like in later years, and also cultural habits have a big influence.

Food is also a very important way to express social relations. Hospitality is expressed by offering food and drinks to visitors and friends. It is also a way to distinguish oneself by (not) eating certain foods, usually dictated by religion.

The Future of Food

We have discussed briefly the various aspects of food production, processing, distribution, and consumption. The keywords are food security (is there enough food), food safety (is the available food safe to consume), and food quality (is the food of such a quality that it can fulfill the need of the consumer). Humankind is capable to produce enough food for the whole world population; in other words, food security can be realized, in principle. In practice, however, this appears not to be possible due to socioeconomic and political problems. Food safety and food quality are manageable, again in principle. The question is now how future developments can help in increasing food security, food safety, and food quality. A rapidly upcoming problem related to food production is sustainability: Are we able to produce food in such a way that also future generations are able to fulfill their needs of food without depleting Mother Earth?

Food and Sustainability

The key sustainability issues in food production are optimal use of raw materials (with as little waste as possible while still satisfying consumer demands), efficient usage of water, energy, packaging materials, and processing aids, and economic efficiency in line with social and cultural values. A recent concern is that the production of meat and milk is contributing considerably to environmental problems. One reason is the emission of gases that are involved in climate change problems (especially methane). Another reason is the inefficient conversion of plant proteins in animal feed into animal proteins for human consumption (Aiking et al., 2006). This problem is complicated and the simple solution is not to cut down animal production in developing countries, as the contribution of small-scale animal farming to livelihood: animals, which are a major source of food,

provide fuel and manure to be used as fertilizer in developing countries. In the industrialized world, however, developments of meat alternatives are a possible solution or part of a solution. It could also be of interest for upcoming countries such as India and China.

Food and Health

The relationship between food, nutrition, and health is obvious on the one hand, but much is still unknown. First of all, an individual food cannot be called unhealthy or healthy, but diets can. In other words, it is the combination of several foods in a diet that determines what is healthy. In developing countries, health problems are related mainly to insufficient energy intake and lack of micronutrients. In the developed world, the main problem is overconsumption and too little fiber. Too many calories are taken in with a minimum of physical exercise, thus leading to obesity and ultimately to so-called "diseases of civilization" such as coronary heart disease and diabetes. It is not only food, by the way, but also lifestyle that determines the incidence of obesity. Incidentally, obesity is also increasing in certain populations in the developing world. Obviously, health is also related to food safety if microorganisms cause diarrhea with associated problems, and other food intoxications.

THE ROLE OF FOOD TECHNOLOGY

How could food technology help to alleviate some of the problems that we face? First of all, knowledge of what causes postharvest losses will help to tackle this problem. It is estimated that 30 to 40% losses occur in developing countries and, therefore, measures to avoid this will have a big effect on food security as well as on food safety (Engstrom and Carlsson-Kanyama, 2004; Kader, 2005). One of the problems with postharvest spoilage is that microorganisms produce toxins (such as the carcinogenic compound aflatoxin) that are really very dangerous to human health (Williams et al., 2004). Prevention of this would definitely help increase food security as well as safety (Ortiz et al., 2008).

Second, when raw materials are processed into foods, desired and undesired things happen. Desired effects are increased digestibility, increased food safety because of elimination of pathogens, and increased shelf life. Undesired effects are destruction of essential nutrients, and losses of resources (excessive waste). Because lack of micronutrients is a serious problem in the developing world (Kennedy et al., 2003), making micronutrients more bioavailable, possibly by adding them to food, and preventing losses of these compounds, would make a major contribution to alleviate inadequate nutrition.

Third, if food processing of local crops can be connected to demand of urban consumers—that is, by aligning food processing to consumers' wishes—this link would offer the opportunity to raise income and earn a living for the local processors and producers. In doing so, it is essential that food safety and quality can be guaranteed. Food technology can help in realizing this.

Fourth, institutional barriers to access markets (regionally and internationally) could be tackled by investing in quality and safety by technological measures, and to have knowledge about the products produced so that real safety problems can be distinguished from trade barriers in disguise.

A very important aspect with all preservation technologies is packaging. It forms the barrier between the food and its environment, and it can protect the food from recontamination and other undesired influences from the environment (such as oxygen). Packaging has therefore a large effect on food quality as well as on food safety. Food technology can help in adjusting packaging technology to what is needed for a particular food.

FOCUSING THE AGRI-FOOD RESEARCH AGENDA OF THE 21ST CENTURY

Table 2 highlights some issues related to food security and safety, the link between food and health, and sustainability of agro-ecosystems for both the industrialized and the developing world. In this regard, agri-food system research should focus on using better local crops for food production, reducing postharvest losses substantially, optimizing local processing in such a way that the nutritional value (especially bioavailability of micronutrients) is improved as well as the eating quality, linking local production and processing to urban consumers by delivering safe, nutritious, and good-quality food according to consumers' demands, improving processing and storage or packaging to ensure food safety (i.e., absence of pathogens and contaminating chemicals), dealing with institutional barriers for access to markets, and making more sustainable global food production systems.

CONCLUSIONS

This background article for the Science Forum 2009 has provided some scenarios of the future of food for the mid-21st century. This article has also briefly addressed the major developments in food production, especially the possible role of food technology, and based on this analysis, some issues for shaping a priority agri-food research agenda have been identified. Next to technological issues, it should be realized, however, that institutional barriers can be a major obstacle for the developing world to gain access to local, regional, and global markets. At the same time, it is also clear that technology could help to overcome these institutional barriers by making it possible to produce high-quality, safe, and nutritious food. If it is possible to realize such a development, it should also be possible to reduce poverty by linking urban food demand in the developing world to local food production.

Table 2. Overview of relevant issues for future of food and the role of technology.

Issue	Developing world	Developed world
Food security	Is a big issue Postharvest losses Postprocessing packaging and storage	No issue anymore: tackled by industrialization of food production
Food safety	Pathogenic microorganisms Contaminating chemicals (pesticides, environmental contaminants such as dioxin, PCBs†)	Mainly pathogenic microorganisms
Food and health	Micronutrients Macronutrients	Overconsumption leading to obesity and associated health problems
Sustainability	Soil depletion and use of fertilizers Water quality Waste of food	Fossil energy use Water use Making better use of resources Waste of food

†PCBs, polychlorinated biphenyls.

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