Chapter 3

How can climate change and the development of bioenergy alter the long-term outlook for food and agriculture?

Günther Fischer[1]

Accumulating scientific evidence has alerted international and national awareness to the urgent need to mitigate climate change. Meanwhile, increasing and reoccurring extreme weather events devastate more and more harvests and livelihoods around the world.

Biofuels development has recently received increased attention as a means to mitigate climate change, alleviate global energy concerns and foster rural development. Its perceived importance in these three areas has made biofuels feature prominently on the international agenda. Nevertheless, the rapid growth of biofuel production has raised many concerns among experts worldwide, particularly regarding sustainability issues and the threat posed to food security (FAO, 2008a).

As recent events have shown, a number of factors – including the adoption of mandatory biofuel policies, high crude oil prices, increasing global food import demand, below average harvests in some countries and low levels of world food stocks – have resulted in sudden and substantial increases in world food prices. The consequences have been food riots around the world, from Mexico and Haiti to Mauritania, Egypt and Bangladesh. Estimates indicate that high food prices increased the number of food-insecure people by about 100 million.

This chapter presents an integrated agro-ecological and socio-economic spatial global assessment of the interlinkages among emerging biofuel developments, food security and climate change. Its purpose is to quantify the extent to which climate change and expansion of biofuel production may alter the long-term outlook for food, agriculture and resource availability, based on work

1. The work summarized in this chapter uses the modelling tools and databases developed by the Land Use Change and Agriculture Programme at IIASA. In particular, the chapter benefited from the model and data development and analysis carried out in the frame of a major global study on biofuels and food security (Fischer *et al.*, 2009), commissioned by the Organization of the Petroleum Exporting Countries (OPEC) Fund for International Development (OFID). The author is grateful to colleagues Sylvia Prieler, Eva Hizsnyik, Mahendra Shah and Harrij van Velthuizen for their contributions and comments.

by FAO in its *World agriculture towards 2030/2050* assessment (Chapters 1 and 6 in this volume; FAO, 2006).

The International Institute for Applied Systems Analysis (IIASA) has developed a modelling framework and models to analyse the world food and agriculture system spatially and to evaluate the impacts and implications of agricultural policies. The modelling framework has recently been extended and adapted to incorporate biofuel development issues. A brief summary of the methods and models applied in this study is presented in the following section.

Methodology and data

The modelling framework

The analysis is based on a state-of-the-art ecological-economic modelling approach. The quantified findings of the scenario-based study rely on a modelling framework that includes the FAO/IIASA Agro-Ecological Zone (AEZ) model and the IIASA World Food System (WFS) model. The modelling framework encompasses climate scenarios, agro-ecological zoning information, demographic and socio-economic drivers, and production, consumption and world food trade dynamics (Fischer *et al.*, 2009; 2005). A summary of the main model components is provided in Annex 3.1.

This modelling framework comprises six main elements, as shown in Figure 3.1:

- A storyline and quantified development scenario is selected (usually from the extensive integrated assessment literature) to inform the WFS model about demographic changes in each region and projected economic growth in non-agricultural sectors. It also provides assumptions broadly characterizing the international setting (e.g., trade liberalization, international migration) and the priorities for technological progress. It quantifies selected environmental variables, such as greenhouse gas emissions and atmospheric concentrations of carbon dioxide (CO_2). In this study, it also defines scenarios of demand for first- and second-generation biofuels.

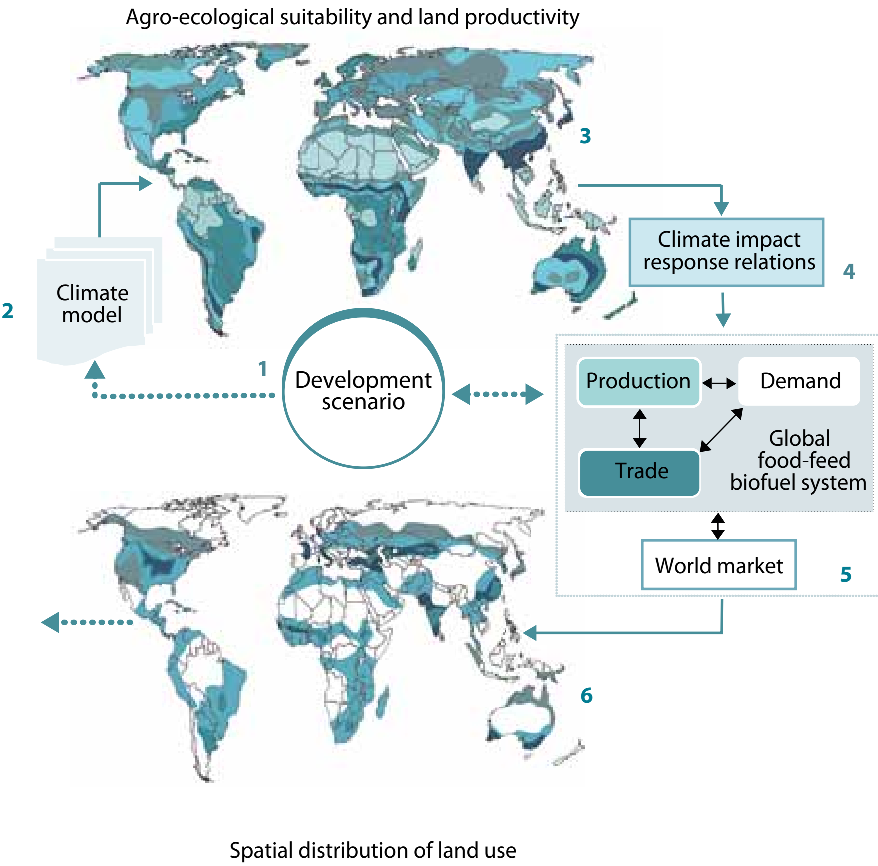
- The emissions pathway associated with the chosen development scenario is used to select from among the available matching published outputs from simulation experiments with general circulation models (GCMs). The climate change signals derived from the GCM results are combined with the observed reference climate to define future climate scenarios.

- The AEZ method is based on a selected climate scenario, estimates the likely agronomic impacts of climate change using a spatial grid of 5′ by 5′ latitude/longitude, and identifies adaptation options.

- Estimated spatial climate change impacts on yields of all crops are aggregated and incorporated into the parameterization of the national crop production modules of a regionalized WFS model.
- The global general equilibrium WFS model – informed by the development storyline and estimated climate change yield impacts – is used to evaluate internally consistent WFS scenarios.

In a final step, the results of the world food system simulations are downscaled to the resource database's spatial grid for quantification of land cover changes and further analysis of the environmental implications of biofuel feedstock production.

Figure 3.1
Framework for ecological-economic world food system analysis



Source: Author.

Potential impacts on the production, consumption and trade of agricultural commodities resulting from climate change and/or a rapid expansion of global biofuel use were evaluated in two steps. First, simulations were developed to represent possible futures where biofuel production was abandoned or frozen at current levels (i.e., as in 2008) and kept constant throughout the simulation period. Second, climate change impacts and alternative levels of biofuel demand, derived from different energy scenarios, were simulated with the WFS model and compared with the respective outcomes without additional biofuel demand or climate change.

The primary role of a reference scenario is to provide a neutral point of departure from which various scenarios take off as variants, with the impact of climate change and/or biofuel expansion being defined by the deviation of the simulation run from the outcomes of the reference scenario. The simulations were carried out yearly for 1990 to 2080.

Baseline assessment

Before turning to the impacts simulated for different assumptions regarding biofuel expansion and climate change, this section summarizes the results from a baseline projection. For this neutral point of departure, the FAO-REF-00 scenario[2] was selected, which assumes a system where no agricultural crops are used as feedstock for biofuel production and where current climate conditions prevail.

Population increase and economic growth

In the long run, the increase in demand for agricultural products is largely driven by population and economic growth, especially in developing countries. Over the next two decades, world population growth is projected at about 1 percent a year, with most of the increase being in developing countries. Population increase is an exogenous input in the model analysis. The most recent United Nations (UN) population projections available (UN, 2009), summarized in Table 3.1, were used. Details of regional groupings in the WFS model are shown in Annex 3.2.

Economic performance in the baseline projection for FAO-REF-00 is shown in Table 3.2. For the analysis reported here, the economic growth characteristics were calibrated by country or regional group to match basic assumptions in the FAO perspective study based on information provided by the World Agriculture Towards 2030/2050 study group at FAO (J. Bruinsma, May 2009, personal communication).

2. Details of the various scenarios are given in Table 3.26.

Table 3.1
Population development

Region	Total population (million people)					
	2000	2010	2020	2030	2040	2050
North America	306	337	367	392	413	430
Europe and Russian Federation	752	762	766	761	748	729
Pacific OECD	150	153	152	148	142	135
Sub-Saharan Africa	655	842	1 056	1 281	1 509	1 723
Latin America	505	574	638	689	725	744
Near East and North Africa	303	370	442	511	575	629
East Asia	1 402	1 500	1 584	1 633	1 630	1 596
South and Southeast Asia	1 765	2 056	2 328	2 553	2 723	2 839
Rest of world[a]	210	233	249	262	272	280
Developed	1 141	1 177	1 202	1 211	1 210	1 198
Developing	4 696	5 417	6 132	6 758	7 257	7 627
World	6 047	6 827	7 582	8 231	8 739	9 105

[a] The regionalization used in the WFS model is described in Annex 3.2.

Source: UN, 2009.

Table 3.2
GDP at constant 1990 prices, baseline projection FAO-REF-00

Region	GDP *(billion USD at constant 1990 prices)*					
	2000	2010	2020	2030	2040	2050
North America	8 286	10 582	12 427	13 817	15 480	17 050
Europe and Russian Federation	7 502	9 487	11 621	14 037	16 860	19 832
Pacific OECD	3 795	4 304	4 781	5 173	5 534	5 888
Sub-Saharan Africa	238	350	531	808	1 236	1 894
Latin America	1 450	2 014	2 822	4 267	6 284	8 828
Near East and North Africa	597	850	1 212	1 772	2 623	3 845
East Asia	1 596	4 165	8 037	13 106	18 373	24 625
South and Southeast Asia	1 255	2 020	3 136	4 840	7 293	10 139
Rest of world	2 418	3 000	3 640	4 343	5 103	5 913
Developed	19 583	24 372	28 830	33 028	37 875	42 770
Developing	5 135	9 399	15 738	24 795	35 810	49 331
World	27 136	36 771	48 207	62 165	78 788	98 014

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

While the recent economic growth rates of more than 8 percent a year in China and India may have been dented by the recent world financial crisis, relatively robust economic growth in China, India and other middle-income developing countries is expected in the next two decades.

Agricultural demand and production

Crop production is driven by developments in yields and crop areas. In many developing countries, the crop yields for most commodities are lower than those attained in developed countries (Table 3.3). At the global level, grain yields increased by an average of about 2 percent a year in the period 1970 to 1990, but this rate has halved since then.

Table 3.3
Total cereal production and consumption: baseline simulation without climate change and biofuel expansion, FAO-REF-00

	Cereal production *(million tonnes)*				Cereal consumption *(million tonnes)*			
Region	2000	2020	2030	2050	2000	2020	2030	2050
North America	474	588	645	707	304	354	376	404
Europe and Russian Federation	526	552	575	650	545	590	621	684
Pacific OECD	40	48	49	55	46	50	52	52
Sub-Saharan Africa	76	133	172	265	106	179	233	347
Latin America	130	197	221	269	139	196	227	272
Near East and North Africa	55	82	94	122	99	148	179	234
East Asia	423	525	568	636	461	570	620	677
South and Southeast Asia	345	450	496	573	341	453	494	573
Rest of world	75	94	103	125	103	120	128	146
Developed	1 008	1 149	1 229	1 363	858	945	993	1 072
Developing	1 060	1 425	1 590	1 914	1 183	1 596	1 808	2 171
World	2 143	2 668	2 923	3 402	2 144	2 661	2 928	3 388

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

With still considerable population growth in the reference projections of the FAO-REF-00 scenario, total production of cereals increases from 2.1 billion tonnes in 2000 to 2.9 billion tonnes in 2030, and to 3.4 billion tonnes in 2050. While developing countries produced about half the global cereal harvest in 2000, their share in total production increases steadily, reaching 57 percent by 2050. As developing countries' share in global consumption increases from 55 to 64 percent in the reference projection, their net imports of cereals grow over time, from 120 million tonnes in 2000 to about 220 million tonnes in 2030, and to 250 million tonnes by 2050.

Agricultural prices

Real prices of agricultural crops declined by a factor of more than two between the late 1970s and the early 1990s, and then stagnated until about 2002, when food prices started to rise. The long-term trend in declining food prices has had several drivers: population development and slowing demographic growth; technological development and growing input use in agriculture, notably a substantial increase in productivity since the green revolution of the early 1970s; and support policies maintaining relatively inelastic agricultural supply in developed countries.

The index of world food prices increased by 140 percent between 2002 and 2007, primarily as a result of increased demand for cereals and oilseeds for biofuels, low world food stocks, reduced harvests owing to drought conditions in locations such as Australia and Europe, record oil and fertilizer prices, and world market speculation. Since the second half of 2008, agricultural prices have again been decreasing substantially.

The baseline projection of the FAO-REF-00 scenario is characterized by modest increases in world market prices between 2000 and 2050. Table 3.4 shows the projected price indices for crops and livestock products in comparison with 1990 levels for a reference simulation without climate change or the expansion of biofuel production. This is also partly the outcome of an assumed further reduction of agricultural support and protection measures.[3]

Table 3.4
Agricultural prices, baseline projection FAO-REF-00

	Price index *(1990 = 100)*			
Commodity group	2020	2030	2040	2050
Crops	94	99	107	113
Cereals	104	106	114	123
Other crops	90	95	103	108
Livestock products	107	110	115	119
Agriculture	98	102	109	115

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

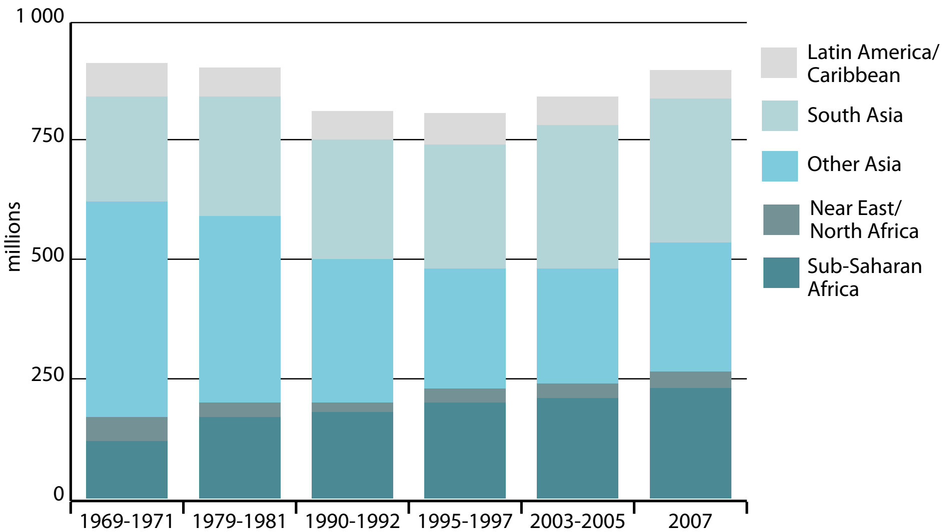
Risk of hunger

In 1970, 940 million people in developing countries – a third of their total population – were regarded as chronically undernourished. Over the following two decades, the number of undernourished people declined by some 120 million, to an estimated 815 million in 1990. The largest reduction occurred in East Asia, where the decline was from 500 million in 1970 to about 250 million in 1990. The numbers of undernourished people increased slightly in South Asia and almost

3. Price dynamics depend critically on assumed long-term rates of technological progress in agriculture. The price trends presented here should therefore not be interpreted as predictions of future price development but as a characteristic of the chosen reference simulation.

doubled in sub-Saharan Africa. The total number of undernourished people in developing countries declined further from 815 million in 1990 to 776 million in 2000. During this period, the number of undernourished in sub-Saharan Africa increased from 168 to 194 million. Africa has the highest proportion of undernourished people, at about 35 percent of the total population, compared with about 14 percent in the rest of the developing world (Figure 3.2).

Figure 3.2
Historical trends in numbers of undernourished people, developing countries



The estimate for 2007 is based on partial data for 2006 to 2008 and uses a simplified methodology, so should be regarded as provisional.
Sources: FAO, 2008b; 2001.

The FAO-REF-00 scenario projects a globally decreasing number of people at risk of hunger (Table 3.5). The projected decrease is most pronounced in East and South Asia. A projected further increase in the number of people at risk of hunger in Africa is expected to result in Africa accounting for 35 percent of the total in 2020 and 40 percent in 2030. Although representing some progress in mitigating hunger, the projected development in scenario FAO-REF-00 is far from sufficient to meet the reductions necessary for achieving the Millennium Development Goal (MDG).

Table 3.5
People at risk of hunger, baseline projection FAO-REF-00

	People at risk of hunger *(millions)*					
Region	2000	2010	2020	2030	2040	2050
Sub-Saharan Africa	196	252	286	271	258	239
Latin America	56	43	31	20	14	10
Near East and North Africa	42	51	57	53	52	47
East Asia	173	139	104	68	42	26
South and Southeast Asia	364	378	362	278	192	136
Developing countries	833	864	839	691	557	458

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Crop and livestock production value added

In the FAO-REF-00 scenario, the global value added of crop and livestock production in 2000 amounts to USD 1 260 billion in 1990 dollars (Table 3.6). This is projected to increase by 30 percent in the 20 years to 2020. In 2030 and 2050 the projected values added amount to respectively USD 1 836 billion and USD 2 192 billion (in 1990 dollars).

Table 3.6
Value added of crop and livestock sector, baseline projection FAO-REF-00

	Value added *(billion USD)*					
Region	2000	2010	2020	2030	2040	2050
North America	166	179	192	203	214	226
Europe and Russian Federation	206	220	235	245	255	264
Pacific OECD	47	52	57	62	67	71
Sub-Saharan Africa	65	82	105	133	165	198
Latin America	155	190	227	262	289	308
Near East and North Africa	55	70	86	104	122	141
East Asia	249	282	314	342	365	384
South and Southeast Asia	252	299	348	400	450	498
Rest of world	65	71	78	85	93	101
Developed	419	451	483	510	535	561
Developing	775	923	1 081	1 241	1 391	1 530
World	1 259	1 445	1 642	1 836	2 019	2 192

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Cultivated land

Some 1.6 billion ha of land is currently used for crop production, with nearly 1 billion ha under cultivation in the developing countries. During the last 30 years, the global crop area expanded by some 5 million ha a year, with Latin America accounting for 35 percent of this increase. The potential for arable land expansion exists predominantly in South America and Africa, where just seven countries account for 70 percent of this potential. There is relatively little scope for arable land expansion in Asia, which is home to some 60 percent of the world's population.

Table 3.7
Cultivated area, baseline projection FAO-REF-00

	Cultivated area *(million ha)*					
Region	2000	2010	2020	2030	2040	2050
North America	234	235	236	237	241	244
Europe and Russian Federation	339	337	336	334	334	334
Pacific OECD	57	57	57	57	60	61
Sub-Saharan Africa	226	245	265	284	301	315
Latin America	175	193	208	217	223	224
Near East and North Africa	67	69	70	72	73	74
East Asia	147	146	146	146	145	145
South and Southeast Asia	274	281	286	289	292	293
Rest of world	42	41	40	38	38	37
Developed	604	602	601	602	606	610
Developing	915	960	1 002	1 035	1 063	1 081
World	1 561	1 603	1 643	1 676	1 707	1 727

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Table 3.8
Harvested area, baseline projection FAO-REF-00

	Harvested area *(million ha)*					
Region	2000	2010	2020	2030	2040	2050
North America	196	203	210	215	223	231
Europe and Russian Federation	215	216	218	219	221	223
Pacific OECD	25	26	27	28	30	31
Sub-Saharan Africa	134	152	174	194	214	231
Latin America	126	143	160	171	179	180
Near East and North Africa	42	46	50	53	56	59
East Asia	220	224	228	231	233	234
South and Southeast Asia	312	327	341	350	356	359
Rest of world	35	35	35	35	35	35
Developed	421	429	438	446	457	468
Developing	850	909	968	1 016	1 055	1 080
World	1 306	1 373	1 441	1 497	1 547	1 583

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Projected global use of cultivated land in the FAO-REF-00 baseline scenario increases by about 165 million ha from 2000 to 2050. While aggregate arable land use in developed countries remains fairly stable, practically all of the net increases occur in developing countries. Africa and South America together account for 85 percent of the expansion of cultivated land (Table 3.7).

Cultivated land represents the physical amount of land used for crop production. In practice, part of this land is left idle or fallow, and part is used to produce more than one crop within a year. The total harvested area in the FAO-REF-00 scenario is shown in Table 3.8. The implied cropping intensity in the baseline projection increases from about 84 percent in 2000 to 89 percent in 2030, and to 92 percent in 2050.

Climate change impacts on crop suitability and production potential

Climate change and variability affect thermal and hydrological regimes, which in turn influence the structure and functionality of ecosystems and human livelihoods.

Scenarios of climate change have been developed to estimate the effects on crop yields, land areas with cultivation potential, and the numbers and types of crop combination that can be cultivated. A climate change scenario is defined as a physically consistent set of changes in meteorological variables, based on generally accepted projections of CO_2 (and other trace gas) levels.

For the spatial assessment of agronomic impacts of climate change on crop yields under the AEZ family of crop models, climate change parameters are computed for each grid point of the resource inventory by comparing the GCM monthly mean prediction for the given decade with those corresponding to the GCM baseline climate of 1960 to 1990. Such changes (e.g., differences in temperature, ratios of precipitation) are then applied to the observed climate for 1960 to 1990 used in AEZ, to generate future climate data as a plausible range of outcomes in terms of likely future temperatures, rainfall, incoming sunlight, etc. for the nominal years 2025 (termed the 2020s), 2055 (the 2050s) and 2085 (the 2080s).

The range of results computed in AEZ refers to different assumptions concerning autonomous adaptation in cropping and the effects of CO_2 fertilization on crop yields (Table 3.9). The first variant is quantified without considering the effects of CO_2 fertilization, and assumes that farmers would be able to change cropping dates and crop types but would be limited to local crop varieties, i.e., those with the same temperature characteristics and moisture requirements as the land utilization types (LUTs) used in the current climate. The second variant refers to results when CO_2 fertilization is still not considered, but best adapted plant types, such as those available elsewhere and adapted to higher temperatures, are available to maximize production potential. Variants 3 and 4 take into account the effects of CO_2 fertilization and quantify the outcomes with limited and full adaptation of crop types, respectively.

The results presented in Table 3.9 are based on a spatial climate change scenario derived from outputs of the United Kingdom's HadCM3 model (Gordon *et al.*, 2000; Pope *et al.*, 2000) for the IPCC SRES A2 emissions pathway (Nakicenovic and Swart, 2000).

Table 3.9
Impacts of climate change on production potential of rainfed wheat on current cultivated land, Hadley A2 (2050s)

		Change with respect to reference climate *(%)*			
Region	Cultivated land *(million ha)*	Without CO_2 fertilization: current crop types	Without CO_2 fertilization: adapted crop types	With CO_2 fertilization: current crop types	With CO_2 fertilization: adapted crop types
North America	230	-9	-9	-3	-3
Europe	179	-4	-4	3	3
Russian Federation	126	-1	-1	5	5
Central America and Caribbean	43	-48	-57	-45	-54
South America	129	-24	-26	-20	-22
Oceania and Polynesia	53	11	12	16	18
North Africa and West Asia	59	-8	-7	-2	-1
North Africa	19	-16	-14	-11	-9
West Asia	40	-4	-4	2	2
Sub-Saharan Africa	225	-56	-61	-54	-59
Eastern Africa	83	-59	-65	-57	-63
Central Africa	38	-76	-80	-75	-80
Southern Africa	17	-44	-47	-41	-44
Western Africa	86	-98	-99	-98	-98
Asia	519	-16	-17	-11	-13
Southeast Asia	98	-55	-58	-53	-56
South Asia	229	-40	-43	-37	-40
East Asia and Japan	151	-8	-9	-3	-5
Central Asia	41	15	15	21	21
Developed	591	-5	-5	1	2
Developing	972	-22	-24	-18	-20
World	1 563	-10	-11	-5	-5

Source: GAEZ 2009 simulations, May 2009.

Except for countries in Central Asia, the impact of climate change on wheat production in developing countries is generally negative. In contrast, the rainfed wheat production potential of current cultivated land in Europe, the Russian Federation and Oceania is increasing. The net global balance is projected to be a reduction of production potential of 5 to 10 percent by the 2050s.

Table 3.10
Impacts of climate change on production potential of rainfed maize on current cultivated land, Hadley A2 2050s

		Change with respect to reference climate *(%)*			
Region	Cultivated land *(million ha)*	Without CO_2 fertilization: current crop types	Without CO_2 fertilization: adapted crop types	With CO_2 fertilization: current crop types	With CO_2 fertilization: adapted crop types
North America	230	-5	-1	-2	2
Europe	179	23	23	28	27
Russian Federation	126	61	61	66	67
Central America and Caribbean	43	1	5	5	9
South America	129	-3	2	0	6
Oceania and Polynesia	53	27	30	31	34
North Africa and West Asia	59	31	30	34	34
North Africa	19	51	52	55	56
West Asia	40	23	22	26	25
Sub-Saharan Africa	225	-6	-3	-3	1
Eastern Africa	83	1	5	5	9
Central Africa	38	-4	1	-1	5
Southern Africa	17	-45	-44	-43	-43
Western Africa	86	-8	-5	-5	-1
Asia	519	-2	2	2	6
Southeast Asia	98	2	6	5	9
South Asia	229	-7	-3	-3	1
East Asia and Japan	151	3	7	7	11
Central Asia	41	23	26	26	30
Developed	591	13	15	17	19
Developing	972	-3	1	1	5
World	1 563	2	5	6	9

Source: GAEZ 2009 simulations, May 2009.

Table 3.10 summarizes the simulated AEZ results for rainfed grain maize. The global production potential of current cultivated land under projected HadCM3 climate conditions for the 2050s increases in all four variants, owing to a modest increase (or an only slight aggregated decrease) in the grain maize potential in developing countries and a significant increase in developed regions. Despite this improvement at the global level, there are several regions where maize production potential decreases, including sub-Saharan Africa.

Table 3.11
Impacts of climate change on production potential of rainfed cereals on current cultivated land, Hadley A2 2050s

		Change with respect to reference climate *(%)*			
Region	Cultivated land *(million ha)*	Without CO_2 fertilization: current crop types	Without CO_2 fertilization: adapted crop types	With CO_2 fertilization: current crop types	With CO_2 fertilization: adapted crop types
North America	230	-7	-6	-1	0
Europe	179	-4	-4	3	3
Russian Federation	126	3	3	9	9
Central America and Caribbean	43	-10	-6	-6	-2
South America	129	-8	-3	-4	1
Oceania and Polynesia	53	2	4	6	8
North Africa and West Asia	59	-8	-7	-2	-1
North Africa	19	-15	-13	-10	-8
West Asia	40	-4	-4	1	1
Sub-Saharan Africa	225	-7	-3	-3	1
Eastern Africa	83	-3	2	2	6
Central Africa	38	-7	-2	-3	3
Southern Africa	17	-32	-31	-29	-28
Western Africa	86	-7	-4	-3	1
Asia	519	-3	1	2	5
Southeast Asia	98	-5	-1	-1	4
South Asia	229	-6	-2	-2	2
East Asia and Japan	151	2	6	7	10
Central Asia	41	14	14	19	19
Developed	591	-3	-3	2	3
Developing	972	-5	-2	-1	3
World	1 563	-5	-2	0	3

Source: GAEZ 2009 simulations, May 2009.

The results compiled in Table 3.11 go beyond climate change impacts for single crops. The computations look at all cereal types represented in AEZ (some 118 LUTs covering wheat, rice, maize, barley, sorghum, millet, rye, oats and buckwheat) and determine separately for current and future climate conditions the most productive cereal type in each grid-cell of the spatial resource inventory. Results indicate a somewhat increasing global rainfed production potential, provided that CO_2 fertilization is effective and full adaptation of crop types is achieved; climate change could result in a reduction of about 5 percent of global production if these two conditions are not met. In the latter case, most regions would experience a reduction. At the regional level, results for Southern Africa, North Africa and Central America show the largest negative climate change impacts on rainfed cereal production potential.

Table 3.12 presents results for the temporal dimension of climate change impacts by summarizing simulated results based on HadCM3 for three periods – the 2020s, the 2050s and the 2080s. Numbers shown in the table are the best outcomes of the four variants assuming or not assuming effective CO_2 fertilization and full agronomic crop adaptation.

Table 3.12
Impacts of climate change on production potential of rainfed cereals on current cultivated land with CO_2 fertilization, Hadley A2

	Change with respect to reference climate *(%)*								
	Rainfed wheat			Rainfed maize			Rainfed cereals		
Region	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
North America	-1	-3	-2	7	2	-1	1	0	0
Europe	1	3	-1	22	27	21	1	3	-1
Russian Federation	3	5	-1	54	67	63	5	9	6
Central America	-33	-54	-76	6	9	-1	-1	-2	-15
South America	-14	-22	-33	2	6	5	1	1	-1
Oceania and Polynesia	-8	18	9	12	34	58	-7	8	2
North Africa and West Asia	2	-1	-12	19	34	39	2	-1	-11
North Africa	2	-9	-28	38	56	60	2	-8	-23
West Asia	2	2	-6	12	25	31	2	1	-5
Sub-Saharan Africa	-36	-59	-76	1	1	1	1	1	0
Eastern Africa	-38	-63	-81	6	9	11	3	6	9
Central Africa	-53	-80	-95	5	5	5	2	3	2
Southern Africa	-27	-44	-61	-29	-43	-32	-20	-28	-24
Western Africa	-77	-98	-100	1	-1	-6	1	1	-5
Asia	-7	-13	-31	2	6	4	3	5	3
Southeast Asia	-27	-56	-89	4	9	11	2	4	-1
South Asia	-10	-40	-71	1	1	-2	2	2	-1
East Asia and Japan	-9	-5	-16	1	11	12	1	10	12
Central Asia	10	21	9	25	30	16	16	19	11
Developed	0	2	-1	18	19	16	2	3	1
Developing	-11	-20	-36	2	5	3	2	3	0
World	-3	-5	-12	7	9	7	2	3	0

Source: GAEZ 2009 simulations, May 2009.

Results suggest that for the next decades global rainfed cereal production potential is not threatened by a gradual change of climate as projected by the HadCM3 model for the IPCC SRES A2 emissions scenario, provided that CO_2 fertilization effects materialize and farmers are prepared and empowered to adapt fully to a changing climate. It should also be noted that the results in Table 3.12 do not account for the impacts of possibly increased climatic variability.

Table 3.13 presents results for AEZ-estimated rainfed crop potentials of wheat, maize and sorghum (relative to the reference climate), based on the CSIRO GCM climate projections for IPCC A2 emission pathways. Estimates assume full adaptation of crop types and include effects of CO_2 fertilization due to increased atmospheric CO_2 concentrations. Table 3.14 summarizes changes relative to the crop potentials under current climate and excluding CO_2 fertilization effects on crop yield.

Table 3.13
Impacts of climate change on production potential of major rainfed cereals on current cultivated land with CO_2 fertilization, CSIRO A2

	Change with respect to reference climate *(%)*								
	Rainfed wheat			Rainfed maize			Rainfed sorghum		
Region	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
North America	3	10	7	3	9	7	15	25	28
Europe	2	3	-1	40	47	47	31	41	37
Russian Federation	4	4	-15	64	79	69	60	75	70
Central America	-19	-36	-53	2	7	13	3	10	17
South America	-12	-19	-30	2	3	4	8	10	15
Oceania and Polynesia	4	11	4	19	31	57	4	9	7
North Africa and West Asia	2	-1	-12	42	71	69	11	17	13
North Africa	1	4	-18	66	160	183	12	31	20
West Asia	3	-3	-9	33	38	26	11	12	9
Sub-Saharan Africa	-27	-45	-69	0	-2	-7	1	0	-4
Eastern Africa	-30	-48	-72	3	4	-1	4	4	-2
Central Africa	-34	-58	-84	2	2	-1	5	6	7
Southern Africa	-18	-34	-58	-26	-47	-51	-24	-41	-45
Western Africa	-76	-98	-100	0	-1	-7	1	2	-1
Asia	-8	-23	-45	0	1	0	3	5	4
Southeast Asia	-35	-48	-79	0	0	1	-2	-5	-5
South Asia	-22	-45	-70	-1	-3	-5	1	0	0
East Asia and Japan	-7	-21	-38	2	5	2	5	11	11
Central Asia	19	18	-7	34	87	110	27	35	31
Developed	3	7	0	23	30	29	27	38	37
Developing	-10	-23	-42	1	1	0	4	5	4
World	-1	-3	-13	8	10	9	12	16	16

Source: GAEZ 2009 simulations, May 2009.

Table 3.14
Impacts of climate change on production potential of major rainfed cereals on current cultivated land without CO_2 fertilization, CSIRO A2

	Change with respect to reference climate *(%)*								
	Rainfed wheat			Rainfed maize			Rainfed sorghum		
Region	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
North America	0	4	-3	2	5	2	12	20	21
Europe	-1	-3	-11	37	42	40	29	35	30
Russian Federation	1	-2	-23	61	73	62	57	68	62
Central America	-21	-39	-57	0	3	7	1	6	11
South America	-14	-23	-36	0	-1	-1	6	6	10
Oceania and Polynesia	2	6	-4	17	27	50	2	6	3
North Africa and West Asia	0	-7	-19	41	66	62	9	14	8
North Africa	-2	-2	-25	64	153	171	10	27	15
West Asia	0	-9	-17	32	34	21	9	8	5
Sub-Saharan Africa	-28	-47	-72	-2	-5	-12	-1	-3	-8
Eastern Africa	-31	-50	-74	1	0	-7	2	0	-7
Central Africa	-35	-60	-85	1	-1	-6	3	3	2
Southern Africa	-20	-37	-61	-27	-49	-54	-25	-43	-48
Western Africa	-76	-98	-100	-1	-5	-12	0	-2	-6
Asia	-10	-27	-49	-1	-2	-5	2	1	-1
Southeast Asia	-36	-51	-80	-2	-4	-4	-4	-7	-9
South Asia	-23	-47	-72	-3	-7	-10	-1	-4	-5
East Asia and Japan	-9	-24	-43	0	1	-3	3	7	5
Central Asia	17	12	-14	33	81	101	25	31	26
Developed	0	0	-10	21	25	22	25	32	30
Developing	-13	-27	-46	-1	-2	-5	2	1	-1
World	-4	-8	-21	6	6	4	10	12	10

Source: GAEZ 2009 simulations, May 2009.

The results of the AEZ analysis using HadCM3 and CSIRO climate projections for IPCC A2 emission pathways suggest three conclusions: i) in a number of regions, climate change poses a significant threat for food production; ii) the global balance of the food production potential from rainfed cereal production on current cultivated land may improve slightly in the short term – farmers' adaptation to a changing climate, and the strength of the CO_2 fertilization effect on crop yields will be decisive factors in realizing a positive global balance of food production potential; and iii) beyond 2050, negative impacts of warming will dominate and cause a rapid decrease of the crop production potential in most regions and for the global aggregate.

In the short term, policy-makers need to strengthen farmers' adaptation capacity and support strategies for coping with climate variability and extreme events that may severely affect the welfare of the most vulnerable populations. In the long run, if climate change is not halted, it will result in irreparable damage to arable land, water and biodiversity resources, with eventually serious consequences for food production and food security.

Impacts of climate change on world food system indicators

The potential impacts of climate change on production and trade of agricultural commodities, particularly cereals, were evaluated in two steps. First, simulations were undertaken in which current climate and atmospheric conditions prevailed. Second, yield impacts due to temperature and CO_2 changes, derived from the agro-ecological assessment, were simulated using the WFS model and compared with the respective outcomes without climate change. Assumptions and results for the reference projection were presented in the section on Baseline assessment.

Data on crop yield changes were estimated with AEZ for different climate change scenarios, and were compiled to provide yield impact parameterizations for the countries or regions covered in the WFS model. Yield variations caused by climate change were introduced into the yield response functions by means of a multiplicative factor with an impact on the relevant parameters in the mathematical representation (i.e., the crop yield functions).

Exogenous variables, population growth and technical progress were left at the levels specified in the respective reference projections. No specific adjustment policies for counteracting altered agricultural performance were assumed beyond the farm-level adaptations resulting from economic adjustments by individual actors in the national models The adjustment processes in the different scenarios are the outcome of the imposed yield changes triggering changes in national production levels and costs, leading to changes in agricultural prices in international and national markets; these in turn affect investment allocation and labour migration among sectors and within agriculture.

Agricultural prices

Table 3.15 summarizes the outcomes of scenario simulations with regard to agricultural prices. It shows the price index deviations, as percentages, relative to the equilibrium prices calculated in the reference projection without climate change. Price indices were calculated for cereals, overall crops and the aggregate of crop and livestock production. Climate scenarios were constructed for both the HadCM3 (Gordon *et al.*, 2000; Pope *et al.*, 2000) and the CSIRO (Gordon and O'Farrell, 1997; Hirst, Gordon and O'Farrell, 1997) GCM model outputs of

IPCC SRES A2 simulations. Table 3.15 gives the results for simulations using the Hadley Centre climate model outputs with and without the effects of CO_2 fertilization on crop yields. Again, the climate scenarios do not take into account the possibility of increased climate variability, and the results assume successful and full agronomic adaptation by farmers.

Table 3.15
Impacts of climate change on agricultural prices

Scenario	*CO_2 fertilization*	Change in price index relative to reference climate *(%)*			
		2020	2030	2050	2080
Cereals					
Hadley A2	with	-4	-1	-1	23
Hadley A2	without	1	6	10	44
CSIRO A2	with	1	3	2	21
Crops					
Hadley A2	with	-4	-3	-3	11
Hadley A2	without	0	4	7	27
CSIRO A2	with	-1	0	0	9
Agriculture					
Hadley A2	with	-3	-2	-2	8
Hadley A2	without	0	3	5	20
CSIRO A2	with	-1	1	0	7

Source: IIASA WFS simulations, May 2009.

Overall, climate change yield impacts have only a small impact on world market prices in the decades until about mid-century. In fact, the CO_2 fertilization effect and assumed autonomous adaptation to climate change more than compensate for negative yield impacts. Beyond 2050, negative yield impacts dominate and cause price increases, simulated at about 20 percent for cereals in the 2080s. When CO_2 fertilization effects are disregarded, prices start to increase gradually in the early decades, and increases are projected to accelerate after 2050. In this case, medium-term effects on cereal prices are in the order of 10 percent; in the long term – by 2080 – simulated price increases approach 50 percent.

Cereal production and consumption

The impacts of climate change on the production of cereals, resulting from both changes in land productivity and the economic responses of actors in the system, are summarized in Table 3.16.

The model results present a fairly consistent response to climate change and geographical patterns in regional cereal production. At the global level, taking into account economic adjustment of actors and markets, cereal production until 2050 is about 1 percentage point lower than it is when both CO_2 fertilization and agronomic adaptation are considered. For the 2080s the differences exceed 2 percentage points in both the HadCM3 and the CSIRO climate scenarios. When CO_2 fertilization effects are not considered, simulated global cereal production is 1.4 percent lower than the baseline in 2050 and more than 4.3 percent lower in 2080 (representing about 165 million tonnes).

Table 3.16
Impacts of climate change on cereal production

	Change relative to reference scenario *(%)*											
	Hadley A2				CSIRO A2				Hadley A2, without CO_2 fertilization			
Region	2020	2030	2050	2080	2020	2030	2050	2080	2020	2030	2050	2080
North America	1.9	-2.9	-2.9	-0.8	2.8	0.1	5.8	7.1	0.9	-3.9	-4.6	-4.8
Europe and Russian Federation	0.8	2.0	1.8	1.5	0.5	1.7	1.0	3.1	0.1	1.0	0.1	-1.1
Pacific OECD	-2.2	2.4	9.5	14.0	2.5	6.9	7.0	18.2	-1.8	2.8	9.3	13.6
Sub-Saharan Africa	-1.3	0.3	-2.0	-2.5	-0.6	0.4	-2.9	-7.2	-0.9	0.6	-2.0	-2.2
Latin America	0.9	4.7	5.5	6.0	1.3	3.5	-0.7	0.9	1.3	5.0	6.4	8.0
Near East and North Africa	-0.5	0.7	1.1	-1.0	5.2	7.7	7.4	-1.0	-0.7	0.3	0.3	-2.2
East Asia	0.1	0.7	2.0	-2.8	-2.2	-2.8	-3.4	-7.2	-0.6	-0.4	0.2	-5.3
South and Southeast Asia	-1.3	-1.3	-3.7	-12.2	-4.8	-5.9	-8.9	-12.8	-1.6	-1.9	-4.6	-13.2
Rest of world	-1.6	-1.7	-3.1	-4.6	-2.4	-2.8	-3.4	-4.6	-2.6	-3.4	-6.1	-9.0
Developed	1.2	-0.7	-0.3	0.5	1.7	1.1	4.2	5.9	0.3	-1.7	-2.0	-2.8
Developing	-0.3	0.7	0.2	-3.9	-1.8	-1.8	-4.2	-7.3	-0.6	0.2	-0.6	-4.9
World	0.3	0.1	-0.2	-2.2	-0.4	-0.6	-0.8	-2.1	-0.3	-0.7	-1.4	-4.3

Source: IIASA WFS simulations, May 2009.

Developing countries consistently experience significant reductions of cereal production in all climate scenarios in the long term up to the 2080s. Among the most severely affected regions are South Asia and sub-Saharan Africa.

In the world of the 2050s and 2080s, consumers are assumed to be much richer than they are today and to be largely separated from agricultural production processes. They earn their incomes mainly in the non-agricultural sectors. Therefore, aggregate changes in consumption depend mainly on food prices and income levels rather than on local production conditions. Table 3.17 summarizes the changes in total cereal consumption (food, feed, industrial and seed use, and waste) occurring in the WFS simulations in response to climate change.

Table 3.17 shows a fairly uniform decline in cereal consumption in the 2080s, of about 2 percent globally (representing a reduction of about 80 million tonnes compared with the 3.8 billion tonnes of consumption in the reference simulation) and about 2.5 percent in developing countries, for both climate model scenarios with CO_2 fertilization. In the HadCM3 simulation without CO_2 fertilization effects, the reduction is about 4 percent compared with a reference scenario without climate change.

Table 3.17
Impacts of climate change on cereal consumption

	Change relative to reference scenario *(%)*											
	Hadley A2				CSIRO A2				Hadley A2, without CO_2 fertilization			
Region	2020	2030	2050	2080	2020	2030	2050	2080	2020	2030	2050	2080
North America	0.7	0.3	0.5	-0.4	0.1	-0.3	1.2	1.0	-0.1	-0.8	-1.2	-3.6
Europe and Russian Federation	0.8	0.3	0.1	-1.2	0.1	-0.4	-0.7	-1.4	0.1	-0.6	-1.4	-3.6
Pacific OECD	2.2	0.3	1.5	-4.5	0.3	-1.5	-0.4	-5.0	0.3	-2.1	-3.2	-12.4
Sub-Saharan Africa	0.4	0.1	-0.1	-4.2	-0.2	-0.5	-0.6	-4.0	-0.2	-0.7	-1.4	-6.8
Latin America	0.8	0.3	-0.1	-2.6	0.1	-0.3	-0.5	-2.3	0.1	-0.4	-0.6	-3.4
Near East and North Africa	0.2	0.0	-0.1	-2.6	-0.2	-0.3	-0.2	-2.4	-0.3	-0.7	-1.1	-4.4
East Asia	0.0	-0.1	0.1	-1.0	-0.4	-0.8	-1.4	-0.8	-0.2	-0.4	-0.7	-1.6
South and Southeast Asia	0.0	-1.1	-1.0	-3.9	-0.9	-1.9	-1.5	-3.6	-0.7	-1.9	-2.0	-5.3
Rest of world	0.3	0.0	-0.1	-0.9	-0.1	-0.4	-0.4	-0.9	-0.1	-0.4	-0.7	-1.7
Developed	0.7	0.2	0.2	-1.6	0.0	-0.5	0.1	-0.8	0.0	-0.9	-1.7	-4.7
Developing	0.2	-0.2	-0.2	-2.5	-0.4	-0.9	-1.1	-2.5	-0.3	-0.8	-1.1	-3.8
World	0.4	-0.1	-0.1	-2.1	-0.2	-0.7	-0.7	-2.0	-0.2	-0.8	-1.2	-4.0

Source: IIASA WFS simulations, May 2009.

Risk of hunger

Estimates of the number of people at risk of hunger vary greatly, depending on socio-economic development trajectories (particularly assumed income levels and income distribution) and population numbers. Assumptions and results for the reference simulation were presented in the section on Baseline assessment. Under this reference projection, the estimated number of undernourished would slowly decrease from 2010, to about 900 million in 2020, 760 million by 2030, 530 million by 2050, and 150 million by 2080. For comparison, changes in the estimated numbers of people at risk of hunger, at different time points and under three different climate scenarios, are summarized in Table 3.18. It is worth noting that in these simulations the recorded climate change impacts on undernourishment are relatively small. In the early periods, this is owing to relatively small global yield impacts and small resulting price effects; in the long term, yield impacts become substantial owing to the improved socio-economic conditions and small absolute number of undernourished.

In summary, climate change impacts on agriculture will increase the number of people at risk of hunger. This impact will be of global significance if imposed on an already high level of undernourishment. In the socio-economic development scenario underlying the projections of *World agriculture: towards 2030/2050* (FAO, 2006), with solid economic growth and a transition to stable population levels after 2050, poverty and hunger, although negatively affected by climate change, are a much less ubiquitous phenomenon than they are today.

Cultivated land

The results for changes in cultivated land use are summarized in Table 3.19, and results for impacts on the harvested area are shown in Table 3.20. As for other food system indicators discussed previously, the changes in net cultivated area simulated in response to climate change scenarios up to 2050 are relatively small. Even when CO_2 fertilization effects are not taken into account, the additional land under cultivation globally is less than 10 million ha. Only after 2050, when climate change impacts become increasingly negative for crop yields, the additional land put into production increases compared with the reference climate simulations. In 2080, the estimated increase is 10 to 13 million ha in simulations with CO_2 fertilization effects accounted for, and 26 million ha in those without CO_2 fertilization. It should be noted that these estimated changes are net global effects and should not be confused with gross land conversion, which can be expected to be a lot higher in response to climate change impacts and adaptation efforts.

Impacts of biofuel expansion on world food system indicators

Biofuels, mainly ethanol and biodiesel, are produced from a number of agricultural crops that are also important for the provision of food and feed. At present, biofuel production is spreading around the world in a growing number of countries.

Several developed countries have embraced the apparent win-win opportunity to foster the development of biofuels in response to the threats of climate change, to lessen their dependency on oil and contribute to enhancing agriculture and rural development. Of course, these issues are also of concern to developing countries, where more than 70 percent of the poor reside in rural areas. Countries such as the United States of America, European Union (EU) countries, China, India, Indonesia, South Africa and Thailand have all adopted policy measures and set targets for the development of biofuels.

Table 3.18
Impacts of climate change on risk of hunger

	Change in number of people at risk of hunger relative to reference scenario *(millions)*								
	Hadley A2			CSIRO A2			Hadley A2, without CO_2 fertilization		
Region	2030	2050	2080	2030	2050	2080	2030	2050	2080
Sub-Saharan Africa	0	1	17	1	0	10	4	9	28
Asia	4	-2	5	22	4	3	27	18	14
Rest of world	-2	-2	6	1	0	5	5	9	16
World	1	-3	28	24	4	19	35	36	57

Source: IIASA WFS simulations, May 2009.

Table 3.19
Impacts of climate change on net use of cultivated land

	Change in cultivated area relative to reference scenario *(million ha)*								
	Hadley A2			CSIRO A2			Hadley A2, without CO_2 fertilization		
Region	2030	2050	2080	2030	2050	2080	2030	2050	2080
Sub-Saharan Africa	0	-1	3	1	0	2	1	2	7
Latin America	-1	-2	1	1	1	3	1	3	8
Other developing	0	0	1	0	0	1	1	1	4
Developed	1	1	5	3	3	6	2	2	6
Developing	-2	-4	5	2	1	7	3	5	19
World	-1	-3	10	4	4	13	5	8	26

Source: IIASA WFS, May 2009.

Table 3.20
Impacts of climate change on harvested area

	Change relative to reference scenario *(million ha)*								
	Hadley A2			CSIRO A2			Hadley A2,without CO_2 fertilization		
Region	2030	2050	2080	2030	2050	2080	2030	2050	2080
Sub-Saharan Africa	-1	-2	4	1	0	2	2	2	10
Latin America	-1	-2	1	1	1	4	1	4	10
Other developing	-1	-2	3	-1	-1	1	1	2	9
Developed	-1	0	6	3	3	6	2	4	9
Developing	-3	-5	8	1	0	7	4	8	29
World	-3	-6	14	4	2	14	6	12	39

Source: IIASA WFS, May 2009.

The main driving forces of biofuel expansion have been huge subsidies and the mandates and targets set by national governments. While the justification for biofuel targets as enhancing fuel energy security and contributing to climate change mitigation and agricultural rural development is appealing, the reality is complex as the consequences of biofuel developments result in local, national, regional and global impacts across interlinked social, environmental and economic domains well beyond the national setting of domestic biofuel targets.

The conditioning factors of biofuel development at the national level include the technical capabilities of biofuels as blending agents; agro-ecological conditions and the availability of land resources; the suitability, productivity and production potential of various biofuel feedstocks; the prospects for regional and international trade of biofuels; and the potential greenhouse gas emission savings and climate change mitigation.

Overview of biofuel scenarios

The biofuel scenarios used in the model simulations were designed to cover a wide and plausible range of possible future demand for biofuels. Scenario specification consisted of three steps: first, an overall energy scenario was selected, including the regional and global use of transport fuels as one of its components; second, pathways were identified based on biofuels' role in the total use of transport fuels; and third, assumptions were defined regarding the role and dynamics of second-generation biofuel production technologies, or conversely the fraction of total biofuel production expected to be supplied by first-generation feedstocks based on conventional agricultural crops (maize, sugar cane, cassava, oilseeds, palm oil, etc.). Data on current biofuel feedstock use, and the assumptions and biofuel scenarios used for the scenario analysis are described in detail in Fischer *et al.* (2009).

Future projections of transport fuel use

The World Energy Outlook (WEO 2008) reference scenario published by the International Energy Agency (IEA, 2008b) was used for describing regional energy futures. In this reference scenario, world primary energy demand grows by an average of 1.6 percent per year from 2006 to 2030, rising from 11 730 million tonnes of oil equivalent (TOE) to slightly more than 17 000 million TOE (or by about 45 percent). This projection embodies the effects of government policies and measures enacted or adopted up to mid-2008. The IEA World Energy Model – a large-scale mathematical system designed to replicate how energy markets function – was the principal tool used to generate sector-by-sector and fuel-by-fuel projections by region or country (IEA, 2008b).

World primary oil demand in the WEO reference scenario increases by about 40 percent, from 76.3 million barrels per day in 2000 to 106.4 million barrels per day in 2030. The transport sector consumes about three-quarters of the projected increase in world oil demand (IEA, 2008b).

In terms of total final consumption of transport fuel, the scenario projects an increase from 1 962 million TOE in 2000 to 3 171 million TOE in 2030. Regional totals of transport fuel consumption, derived from the WEO reference scenario for the period 1990 to 2030 and extrapolated to 2050 for use in the WFS simulations, are summarized in Table 3.21.

Table 3.21
Final consumption of transport fuels, WEO scenario

Region	2000	2020	2030	2050
	(million TOE)			
North America	655	773	773	781
Europe and Russian Federation	519	658	652	609
Pacific OECD	105	110	99	93
Africa	45	69	80	122
East Asia	114	337	495	625
South Asia	111	224	322	544
Latin America	149	253	285	332
Near East and North Africa	108	214	259	342
Rest of world	6	16	24	36
Developed	1 236	1 480	1 460	1 417
Developing	576	1 174	1 529	2 068
World[a]	1 962	2 830	3 171	3 750

[a] World totals include international marine bunkers and international aviation.

Source: IEA, 2008b.

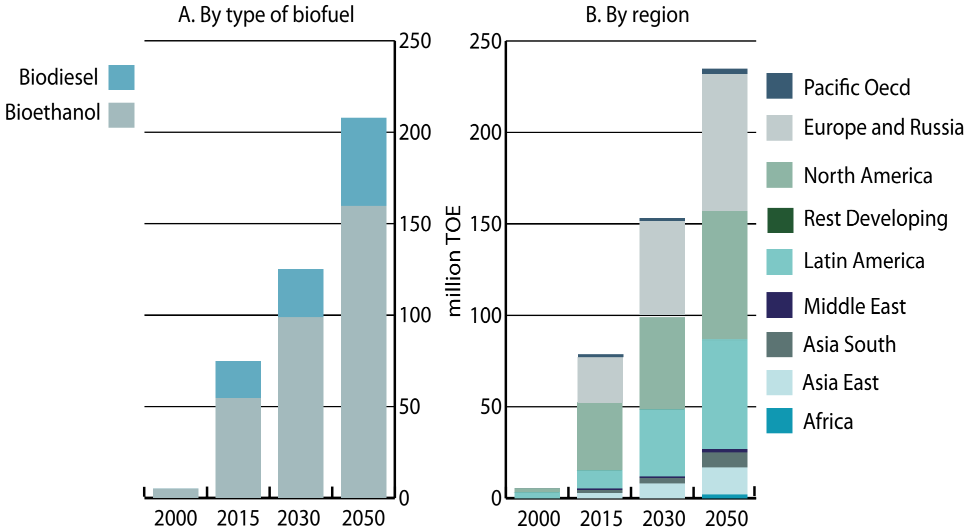
Biofuels use and share in total final consumption of transport fuels

The level and regional pattern of total transport fuel consumption presented in the previous subsection has been applied in all the biofuel simulations with the WFS model discussed in this paper. Regarding biofuel use, two alternative scenarios were implemented: i) biofuel expansion based on the WEO 2008 projections; and ii) fast expansion of biofuel production in accordance with the mandates and targets announced by several developed and developing countries. In addition, a number of sensitivity scenarios were specified to gain understanding over a wide range of possible biofuel production levels to 2050.

Biofuel consumption in the WEO scenario: Final demand for biofuels in 1990 was about 6 million TOE, of which two-thirds were produced in Brazil. In 2006, world biofuel consumption reached 24.4 million TOE, with the United States of America as the largest producer and consumer. In the simulation for 2020, final consumption of biofuels in the developed countries is projected at 63 million TOE, with the United States and the EU27 accounting for 90 percent of this use. In 2030, the final consumption of biofuels reaches 79 million TOE in the developed world. For 2030 and 2050, the projections of biofuel consumption in developed countries amount to 79 and 124 million TOE respectively.

Among the developing countries, Brazil has been the pioneer, producing about 5 million TOE in 1990; this is projected to increase to 18 million TOE in 2020. Total biofuel consumption in developing countries starts from about 5.5 million TOE in 2000, increases to 31 million TOE by 2020, and reaches 46 million TOE in 2030. Biofuel use in developing countries in this scenario is dominated by Brazil throughout the projection period. Brazil, China and India together account for about 80 percent of biofuel use in developing countries, a combined share that decreases slightly, to about 75 percent, in 2050. Figure 3.3 shows the dynamics of projected biofuel consumption in the WEO-based scenario; panel A indicates the fuel split, panel B shows the distribution by region.

Figure 3.3
Final consumption of biofuels, WEO scenario



Source: Fischer *et al.*, 2009.

Biofuels consumption in the target (TAR) scenario: The WEO 2008 report states "… assume in the Reference Scenario that the biofuel mandates in China and the European Union will be met after a lag of a few years but that biofuels in the United States in 2030 will attain only about 40 percent of the very ambitious target in the 2007 Energy Independence and Security Act. Asia and OECD Europe experience faster rates of growth, but in absolute terms these increases trail those in the larger North American market. Biofuels demand in the OECD Pacific region remains modest. Growth in Latin America is moderate, a consequence of the sizeable share of the market in Brazil already held by biofuels" (IEA, 2008b: 172).

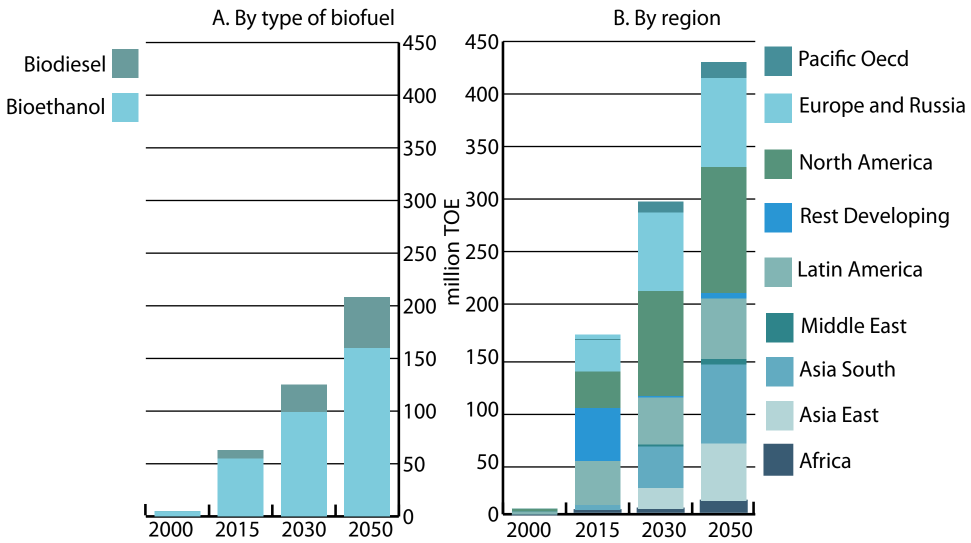
Table 3.22
Voluntary and mandatory targets for transport fuels in major countries

Country/region	Mandatory, voluntary or indicative target
Australia	At least 350 million litres of biofuels by 2010
Canada	5% renewable content in gasoline by 2010
EU	5.75% of biofuel by 2010, 10% by 2020
Germany	6.25% of biofuel by 2010, 10% by 2020
France	7% of biofuel by 2010, 10% by 2015, 10% by 2020
Japan	0.6% of auto fuel by 2010; fossil oil dependence in the transport sector reduced from 98% to 80% by 2030
New Zealand	3.4% of both gasoline and diesel by 2012
United States	12 billion gallons (55 billion litres) by 2010, 20.5 billion gallons (91 billion litres) by 2015, 36 billion gallons (164 billion litres) by 2022; 16 billion gallons (73 billion litres) from advanced cellulosic ethanol
Brazil	Mandatory 25% ethanol blend with gasoline; 5% biodiesel blend by 2010
China	2 million tonnes of ethanol by 2010, 10 million tonnes by 2020; 0.2 million tonnes biodiesel by 2010, 2 million tonnes by 2020
India	5% ethanol blending in gasoline in 2008, 10% in 2009; indicative target of 20% ethanol blending in gasoline and 20% biodiesel blending by 2017
Indonesia	2% biofuels in energy mix by 2010, 3% by 2015, 5% by 2020
Thailand	2% biodiesel blend by 2008, 10% by 2012; 10% ethanol blend by 2012
South Africa	2% of biofuels by 2013

Source: Fischer *et al.*, 2009.

A number of countries have defined mandatory, voluntary or indicative targets for transport fuels (Table 3.22). To gain a better understanding of the possible impacts on the world food system that may result from implementation and full achievement of the specified targets, a second biofuels scenario, more ambitious in terms of biofuel expansion than the WEO outlook, was implemented. In this TAR scenario, final consumption of biofuels increases to 189 million TOE in 2020 (about twice the value achieved in WEO) and climbs to 295 million TOE in 2030 and 424 million TOE in 2050. As hardly any country has announced biofuel targets beyond about 2020, this scenario should be interpreted as the extension of a rapid and ambitious biofuel development pathway based on the targets announced up to 2020. It approximately doubles biofuel consumption compared with the WEO projections. Figure 3.4 shows the distribution of biofuel consumption by type and region under the TAR scenario.

Figure 3.4
Final consumption of biofuels, TAR scenario



Source: Fischer *et al.*, 2009.

It is worth noting that in the TAR scenario the share of developing countries in total biofuel consumption is higher than in the WEO scenario, owing to the fairly ambitious proposed or announced targets for China, India, Indonesia and Thailand. This change in the regional distribution means that biodiesel's share in total biofuels increases somewhat compared with WEO.

Share of biofuel consumption in total transport fuels: In the developed world, the projected share of biofuel consumption in total transport fuels use in 2020 amounts to 4.3 percent in the WEO scenario. By 2030, this share increases to 5.5 percent. For the developing world, the WEO scenario projects biofuel shares in total transport fuel use of 2.7 percent in 2020 and 3.0 percent in 2030. At the global level, the shares come to 3.5 percent in 2020, 4.2 percent in 2030, and 6.0 percent in 2050. With a road transport share of 70 to 75 percent in total transport fuel use, biofuels would account for 4.5 percent of road transport in 2020, 5.4 percent in 2030, and 7.6 percent in 2050.

Share of second-generation biofuels in total biofuel consumption

In recent years, second-generation biofuels using woody or herbaceous non-food plant materials as feedstocks have attracted great attention because they are seen as superior to conventional feedstocks in terms of their greenhouse gas saving potential, while their potential for production on “non-food” land is seen as being even more valuable.

It is widely acknowledged that major technological breakthroughs will be required to improve feedstock materials and the efficiency of the conversion process before second-generation biofuels can make a significant contribution.

To complete the definition of biofuel scenarios in this assessment, three variants for both the WEO and the TAR biofuel scenarios were specified. These represent alternative views/expectations regarding the dynamics of technology deployment for second-generation fuels. The variants are defined on the basis of different pathways for the share of second-generation fuels in total biofuel consumption. Specification was done by broad regions and follows simple and transparent assumptions. The assumptions used for ethanol are summarized in Table 3.23.

The variant V1 (of both WEO and TAR) assumes that second-generation biofuel technologies will be available for commercial deployment in the United States of America by 2015. Lignocellulose conversion will contribute 7.5 percent of total bioethanol by 2020, rising to 25 percent by 2030. In other OECD countries, it is assumed that second-generation conversion plants will take off from 2020, occupying a share of 12.5 percent by 2030. The biofuel champions among developing countries (Brazil, China and India) will also start using second-generation technologies in 2020, but deployment follows a somewhat slower path to reach only 5 percent of total ethanol in 2030. The V2 variant portrays a delayed development of second-generation technologies. Conversion plants are assumed to become available only by 2030, implying that all transport biofuel production up to 2030 relies on conventional feedstocks.

Scenario variant V3 assumes an early and accelerated deployment of second-generation technologies. In TAR-V3, biochemical ethanol processing and Fischer-Tropsch (FT) diesel plants are already available in 2010, and in OECD countries contribute 10 percent of biofuels by 2015, increasing to more than 30 percent in 2020. In developed countries, second-generation biofuels account for about 50 percent of total biofuels in 2030, and more than two-thirds in 2050. China and India follow this development with a short delay. The shares of second-generation biofuels in these two countries are set at 10 percent in 2020, one-third in 2030, and half in 2050. Other developing countries start deploying second-generation plants in 2020, reaching shares of 10 percent in 2030, and 33 percent in 2050.

At the aggregate global level, second-generation biofuel shares in scenario variant WEO-V1 are 3 percent in 2020, 13 percent in 2030, and 30 percent in 2050. In scenario variant TAR-V1, these shares are respectively 2, 12 and 26 percent – somewhat lower than in the WEO scenario owing to the higher shares achieved by developing countries in the TAR scenario. For variant TAR-V3, with an assumed accelerated second-generation development and deployment path, the respective shares are 22, 38 and 55 percent.

Table 3.23
Shares of second-generation biofuels in total biofuels

		Share of second-generation biofuels *(%)*			
Scenario	***Region***	2015	2020	2030	2050
WEO-V1, TAR-V1	United States	Starts	7.5	25	50
	Other OECD	None	Starts	12.5	33
	Russian Federation	None	Starts	5	20
	Brazil/China/India	None	Starts	5	20
	Other developing	None	None	None	None
WEO-V2, TAR-V2	All countries	None	None	Starts	10
WEO-V3	United States	10	24	40	66
	EU27	None	10	33	50
	Other OECD	None	10	33	50
	Russian Federation	None	5	20	40
	China/India	Starts	5	20	40
	Other developing	0	0	10	20
TAR-V3	United States	10	35	55	70
	EU27	10	31	47	67
	Other OECD	10	31	47	67
	Russian Federation	Starts	10	33	50
	China/India	Starts	10	33	50
	Other developing	0	Starts	10	33

Source: Fischer *et al.*, 2009.

Sensitivity analysis of biofuels share in total transport fuels

In addition to the WEO and TAR biofuel scenarios, four sensitivity (SNS) scenarios were computed to scan the WFS model outcomes for a broad range of imposed first-generation biofuel production levels, from 2 to 8 percent in 2020, 2.5 to 10 percent in 2030, and 3 to 12 percent in 2050. Table 3.24 summarizes the assumed shares of first-generation biofuels in total transport fuel use for different scenarios and time points.

Table 3.24
Shares and total amounts of first-generation biofuels

Scenario	Share in total transport fuels (%)			First-generation biofuels consumption (million TOE)		
	2020	2030	2050	2020	2030	2050
SNS-V1	2	2.5	3	54	76	106
SNS-V2	4	5	6	107	151	211
SNS-V3	6	7.5	9	161	227	317
SNS-V4	8	10	12	214	302	423

Source: Fischer *et al.*, 2009.

First-generation biofuel feedstocks demanded in selected biofuel scenarios

Estimates for 2008 indicate that about 80 to 85 million tonnes of cereals were used for ethanol production, mainly maize in the United States of America, and about 10 million tonnes of vegetable oil for biodiesel production, dominated by the EU. In the reference scenario FAO-REF-01, these amounts are kept constant for the simulation period to 2050. The amounts increase in both the WEO and TAR scenario variants. The time path in each scenario variant depends on the level and geographical distribution of biofuel production and on assumptions regarding the availability of second-generation technologies. The amounts of cereals and vegetable oils required for transport biofuel production in 2020, 2030 and 2050 in selected biofuel scenarios are shown in Table 3.25.

Table 3.25
Use of cereals and vegetable oils for biofuel production

Scenario	Cereals (million tonnes)			Vegetable oils (million tonnes)		
	2020	2030	2050	2020	2030	2050
FAO-REF-01	83	83	83	10	10	10
WEO-V1	181	206	246	26	30	44
WEO-V2	192	258	376	26	33	48
TAR-V1	327	437	446	58	85	112
TAR-V3	238	272	262	46	59	61

Source: IIASA WFS simulations, May 2009.

Impacts of first-generation biofuel expansion on food system indicators

This section presents the results of an integrated spatial ecological and economic assessment of the impacts of accelerated expansion of biofuel production, evaluated in the context of the world food economy and global resource base.

Previous sections presented the analysis framework used in this study, and key assumptions regarding economic development and transport energy demand, particularly use of first- and second-generation biofuels. Internally consistent sets of assumptions were formulated as model scenarios and used to quantify the impacts of expanding biofuel use on agriculture and world food system outcomes. A total of ten scenarios were analysed; the acronyms used and a brief description of each are given in Table 3.26.

Table 3.26
Biofuel scenarios analysed in this study

Acronym	*Description*
FAO-REF-00	Starting in 1990, assumes a world with no agricultural crops used for biofuel production.
FAO-REF-01	Assumes historical biofuel development until 2008; biofuels feedstock demand kept constant after 2008; used as a reference simulation with which alternative biofuel scenarios are compared to identify their impacts.
WEO-V1	Assumes transport energy demand and regional biofuel use as projected by IEA in the WEO 2008 reference scenario. Second-generation conversion technologies become commercially available after 2015; deployment is gradual (Table 3.23)
WEO-V2	Assumes transport energy demand and regional biofuel use as projected by IEA in the WEO 2008 reference scenario. Assumes that delayed arrival of second-generation conversion technologies results in all biofuel production until 2030 being based on first-generation feedstocks.
TAR-V1	Assumes transport energy demand as projected by IEA in the WEO 2008 reference scenario. Assumes that mandatory, voluntary or indicative targets for biofuel use announced by major developed and developing countries will be implemented by 2020, resulting in about twice the biofuel consumption projected in WEO 2008. Second-generation conversion technologies become commercially available after 2015; deployment is gradual (percentages as in WEO-V1).
TAR-V3	Assumes transport energy demand as projected by IEA in the WEO 2008 reference scenario. Assumes that mandatory, voluntary or indicative targets for biofuel use announced by major developed and developing countries will be implemented by 2020. Accelerated development of second-generation conversion technologies permits rapid deployment; 33% and 50% of biofuel use in developed countries from second-generation in 2020 and 2030 respectively.
SNS-V1, V2, V3, V4	Sensitivity scenarios assuming low (V1), intermediate (V2), high (V3) and very high (V4) shares of first-generation biofuels in total transport fuels (Table 3.24).

The impacts of additional demand for first-generation biofuels on production, consumption and trade of agricultural commodities – particularly food staples – were evaluated by comparing the results of a range of biofuel expansion scenarios with a reference projection of the WFS simulated without imposing additional biofuel demand. Results of the reference projection are presented in the section on Baseline assessment.

The biofuel expansion scenarios analysed involved several simulation experiments related to two aspects:

- share of transport energy supplied from biofuels;
- sensitivity of results to development speed of second-generation technologies.

As in climate change analysis, all exogenous variables, such as population growth, technical progress and growth of non-agricultural sectors, are left at the levels in the reference projection. No specific adjustment policies to counteract altered performance of agriculture are assumed beyond the farm-level adaptations resulting from economic adjustments by individual actors in the national models. The adjustment processes in the different scenarios are the outcome of the imposed additional biofuel demand causing changes in agricultural prices in international and national markets; these in turn affect investment allocation and labour migration among sectors and within agriculture. Time is an important aspect in this adjustment process.

Agricultural prices

As expected in a general equilibrium WFS model, when simulating scenarios with increased demand for food staples due to the production of first-generation biofuels, the resulting market imbalances at prevailing prices push international prices upwards.

Table 3.27 shows the results for selected scenarios: biofuel demand according to projections in scenario variants WEO-V1 and WEO-V2 (the latter assuming delayed introduction of second-generation technologies); and high biofuel consumption levels under scenario variants TAR-V1 and TAR-V3 (assuming accelerated introduction of second-generation biofuels).

Table 3.27
Impacts of biofuel expansion on agricultural prices

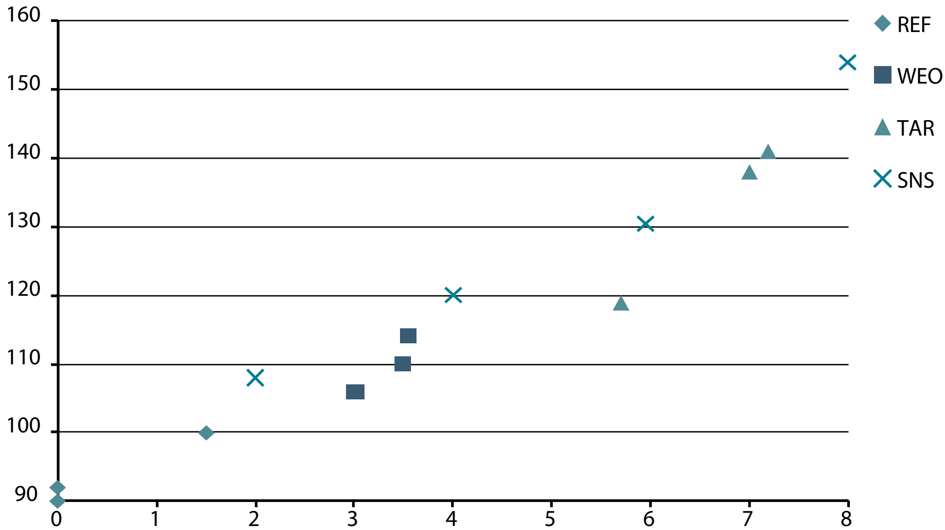
	Change in price index relative to reference scenario FAO-REF-01 *(%)*								
	Cereals			Crops			Agriculture		
Scenario	2020	2030	2050	2020	2030	2050	2020	2030	2050
WEO-V1	11	5	10	10	7	10	8	5	7
WEO-V2	14	13	21	12	11	15	9	8	11
TAR-V1	38	38	27	35	34	27	27	26	20
TAR-V3	19	17	12	22	18	13	17	12	9
SNS-V1	5	5	7	4	5	6	3	3	4
SNS-V2	21	15	21	17	15	18	13	11	13
SNS-V3	37	35	40	30	29	31	24	22	23
SNS-V4	55	58	60	47	47	47	36	36	35

Sources: IIASA WFS simulations; FAO-REF-01 scenario, May 2009.

For 2020, the price increases for both cereals and other crops under the WEO scenario are in the order of 10 percent. As the contribution of second-generation biofuels is still small in WEO-V1, the further delay assumed in WEO-V2 causes only moderate additional crop price increases. For biofuel demand specified in the TAR scenario (which is about twice that projected in the WEO scenario), the impact on crop prices in 2020 is fairly substantial, at about 35 percent. With accelerated introduction of cellulosic ethanol, as assumed in TAR-V3, the price impact on cereals is halved to about 19 percent.

For 2030, the pattern of price impacts remains similar to that of 2020. As second-generation biofuels gain importance towards 2030, the differences in price impacts between WEO-V1 and WEO-V2 become more visible. With accelerated deployment of second-generation fuels, even the large volumes of biofuels produced in TAR-V3 can be achieved with price increases of only about 15 percent.

Figure 3.5
Cereal price index compared with share of first-generation biofuels in transport fuels, 2020



SNS = sensitivity scenarios.
TAR = scenario simulations based on mandates and indicative voluntary targets.
WEO = simulations based on WEO 2008 projections of biofuel demand.
REF = reference projections with constant, decreasing or no biofuel demand beyond 2008.
Source: IIASA WFS simulations, May 2009.

Summarizing these scenario experiments, it emerges that agricultural prices depend considerably on the aggregate share that first-generation biofuels are mandated to contribute to total transport fuel consumption. This is shown in Figure 3.5.

Cereal demand and production

The rising agricultural prices in the biofuel scenarios provide incentives on the supply side for intensifying production and augmenting and reallocating land, capital and labour. At the same time, consumers react to price increases and adjust their patterns of consumption. Figure 3.6 shows the producer responses in cereal sectors under different biofuel scenarios in 2020 and 2030, i.e., the amount of additional cereal production realized in each scenario compared with FAO-REF-01.

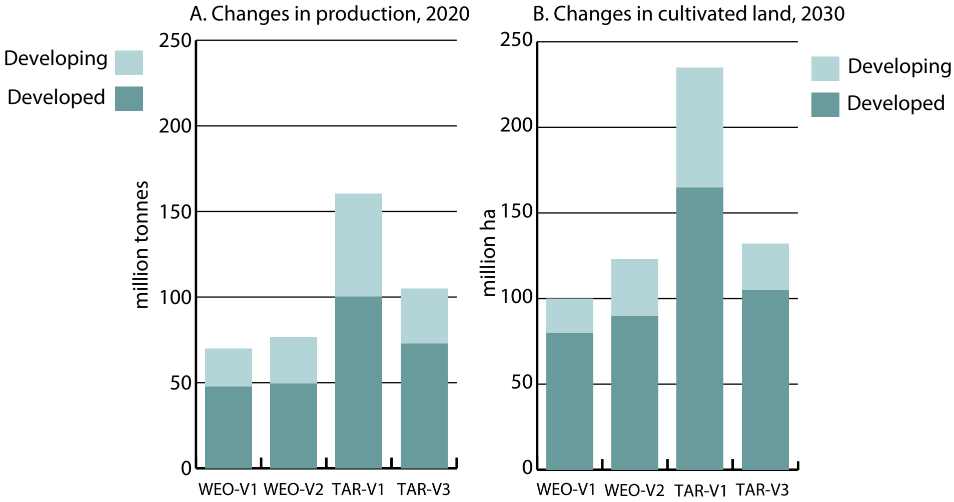
In 2020, compared with 83 million tonnes in 2008 under the reference scenario, the additional global demand for cereal commodities for ethanol production is about 100 million tonnes in WEO-V1 and WEO-V2, 240 million tonnes in TAR-V1 and 155 million tonnes in scenario TAR-V3. Figure 3.6 highlights that the production increases in response to higher agricultural prices are greater in developed countries, as are the reductions in feed use (Figure 3.7). Regarding food use, however, consumption in developed countries is less responsive than in developing countries, which account for 75 percent of the forced reduction in cereal food consumption. Rising food commodity prices tend to have greater negative effects on lower-income than higher-income consumers. First, lower-income consumers spend a larger share of their income on food, and second, staple food commodities such as maize, wheat, rice and soybeans account for a larger share of their food expenditure. Responses on the consumer side, with reduced food and feed use of cereals, are shown in Table 3.28.

Table 3.28
Impacts of biofuel expansion on cereal production and demand

	Change relative to reference scenario FAO-REF-00 (*million tonnes*)								
	2020			2030			2050		
Scenario	Biofuel use	Production	Food/feed	Biofuel use	Production	Food/feed	Biofuel use	Production	Food/feed
FAO-REF-00	83	64	-19	83	66	-17	83	68	-15
WEO-V1	181	134	-46	206	167	-45	246	180	-62
WEO-V2	192	140	-48	258	194	-68	376	271	-102
TAR-V1	327	229	-96	437	308	-133	446	313	-127
TAR-V3	238	174	-59	272	201	-69	262	198	-62

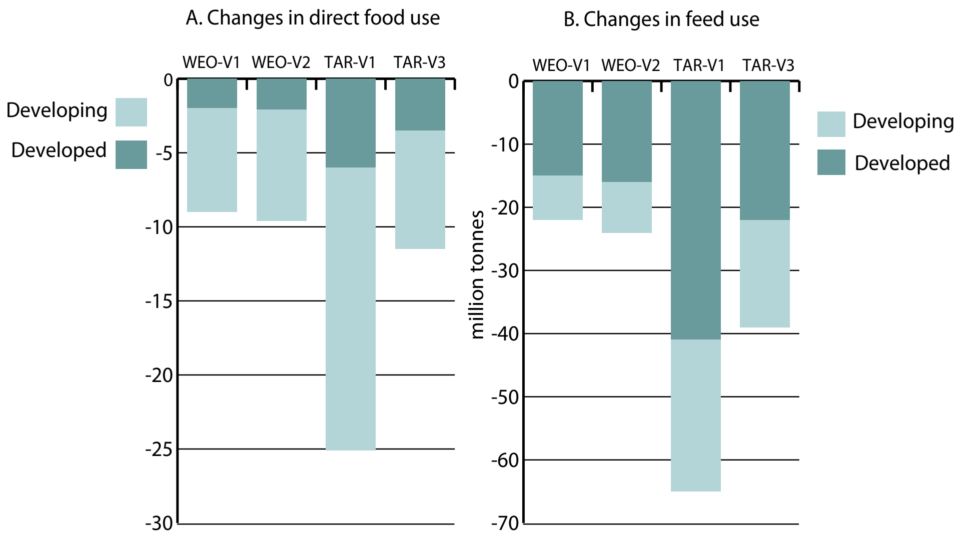
Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Figure 3.6
Changes in cereal production relative to baseline FAO-REF-01



Source: IIASA WFS simulations, May 2009.

Figure 3.7
Changes in cereal use relative to baseline FAO-REF-01, 2020

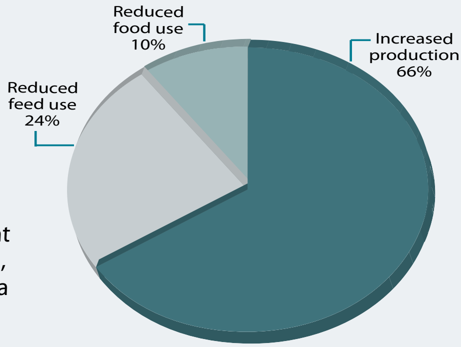


Source: IIASA world food system simulations, May 2009.

Box 3.1 - Where do the cereals needed for biofuel production come from?

On average about two-thirds of the cereals used for ethanol production are obtained from additional crop production.

The remaining one-third comes from consumption changes. The reduction in direct cereal food consumption accounts for 10 percent of the amount of cereals used for biofuel production, reduced feed use accounts for about a quarter.



Risk of hunger

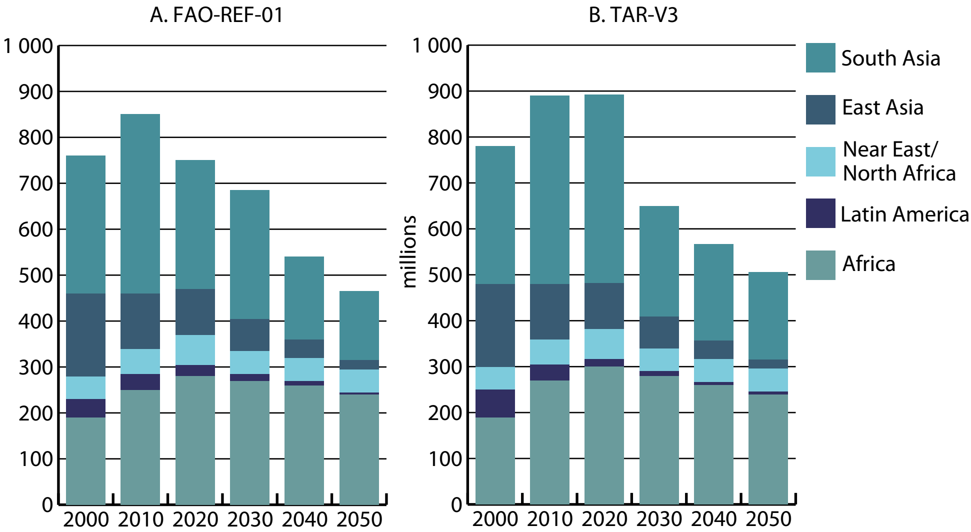
The estimated number of people at risk of hunger used in the WFS model is based on FAO data (FAO, 2001; 2008b) and relies on a strong correlation between the share of undernourished in a country's total population and the ratio of average per capita dietary food supply to average national per capita food requirements.

The model results show that an ambitious biofuel target for 2020, as specified in the TAR scenario, causes higher prices if achieved mainly by production of first-generation biofuels. This reduces food consumption in developing countries, which results in increased numbers of people at risk of hunger. Figure 3.8 compares results until 2050 for the baseline scenario FAO-REF-01 (with no climate change and no additional biofuel demand after 2008) with the estimated numbers of people at risk of hunger in the TAR-V3 scenario (implementing an ambitious global biofuel target with swift introduction of second-generation technologies).

While in FAO-REF-01 the number of undernourished people peaks in 2009/2010 at somewhat more than 890 million and then declines to an estimated 850 million in 2020, 700 million in 2030 and 460 million in 2050, this indicator stays at a high level in the TAR-V3 scenario until 2020, with about 940 million, and only then starts to decline as second-generation production begins to take pressure off the competing food, feed and biofuel feedstock markets.

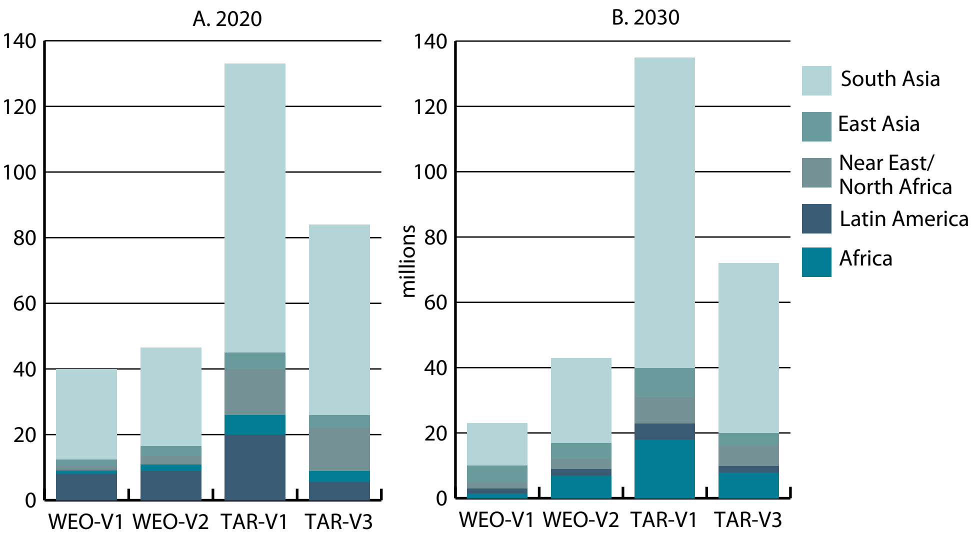
Figure 3.9 presents the simulated regional distribution of additional undernourished people under different biofuel scenarios, showing a particularly large impact in South Asia. It is worth noting that even with relatively swift deployment of second-generation technologies, as assumed in TAR-V3, the results for 2020 show an increase of 80 million undernourished people.

Figure 3.8
People at risk of hunger, developing countries



Source: IIASA WFS simulations, May 2009.

Figure 3.9
Additional people at risk of hunger relative to baseline FAO-REF-01



Source: IIASA WFS simulations, May 2009.

The reference scenario FAO-REF-01 (keeping biofuels consumption constant after 2008) projects that the numbers of undernourished people in developing countries will be 850 million in 2020 and 700 million in 2050. The TAR scenario estimates that an additional 132 million people will be at risk of hunger in 2020 and an additional 136 million in 2030. In the TAR scenario with accelerated second-generation biofuels deployment, the corresponding numbers of additional people at risk of hunger decrease to 85 million in 2020 and 74 million in 2030. Africa and South Asia account for more than two-thirds of these people across biofuel scenarios and in both 2020 and 2030.

Crop and livestock production value added

Biofuel development has been seen as a means to diversify agricultural production and – especially in developed economies – this has shaped agricultural support policies. This study considered the extent to which the additional production of crops as feedstocks for biofuel production will increase value added in agriculture. The percentage changes relative to the reference scenario FAO-REF-00, without any biofuels, are shown in Table 3.29.

Table 3.29
Impacts of biofuel expansion on agricultural value added

	Change relative to reference scenario FAO-REF-00 *(%)*								
	World			Developed countries			Developing countries		
Scenario	2020	2030	2050	2020	2030	2050	2020	2030	2050
FAO-REF-01	1.2	1.2	0.9	2.4	2.9	2.0	0.8	0.7	0.6
WEO-V1	2.5	3.1	3.2	4.3	6.3	5.8	1.8	1.9	2.4
WEO-V2	2.5	3.5	4.0	4.4	7.4	7.8	1.8	2.1	2.9
TAR-V1	4.4	6.6	7.1	6.9	12.1	11.4	3.4	4.4	5.7
TAR-V3	3.7	4.9	4.5	5.7	8.9	7.3	2.9	3.3	3.7

Source: IIASA WFS simulations, May 2009.

Table 3.29 highlights that for all biofuel scenarios, agricultural value added increases at the global and regional levels, as expected. For instance, under WEO-V1 (with relatively modest biofuels development), the changes in absolute terms amount to USD 41 billion in 2020, USD 57 billion in 2030 and USD 71 billion in 2050, in 1990 dollars. Developed countries initially account for about 50 percent of the global gains in agricultural value added. As the relative weight of developed countries in global agriculture decreases over time, so does their share in global gains of agricultural value added, to reach an average of 45 percent in 2050. Table 3.29 shows that agriculture sectors in developed countries also benefit more than those in developing countries in terms of percentage gains relative to the baseline. Under WEO-V1, the increase in 2020 is 4.3 percent for developed countries, compared with only about 1.8 percent for developing countries. While Africa and Latin America achieve gains of 2.4 and 3.1 percent, the gains achieved in the Near East and North Africa and in Asian regions are only 0.9 to 1.9 percent (Table 3.30).

Table 3.30
Impacts of biofuel expansion on regional agricultural value added

	Change in agricultural value added relative to reference scenario FAO-REF-00 *(%)*								
	WEO-V1			WEO-V2			TAR-V3		
Region	2020	2030	2050	2020	2030	2050	2020	2030	2050
North America	8.5	11.2	8.6	8.7	13.2	12.8	11.6	14.1	8.6
Europe and Russian Federation	1.8	3.5	4.6	1.7	4.1	5.3	1.9	6.1	7.3
Pacific OECD	0.8	1.6	1.7	0.8	1.4	1.6	1.7	3.0	2.8
Sub-Saharan Africa	2.4	2.4	2.9	2.4	2.6	3.4	4.2	4.8	4.5
Latin America	3.1	3.5	5.2	3.1	3.8	6.4	4.9	5.7	7.8
Near East and North Africa	1.9	2.1	2.7	2.0	2.2	2.9	3.4	3.9	3.6
East Asia	0.9	1.1	1.2	0.9	1.2	1.4	1.3	1.5	1.7
South and Southeast Asia	1.4	1.4	1.4	1.4	1.4	1.5	2.6	2.8	2.3
Rest of world	1.2	1.2	1.1	1.3	1.4	0.5	2.6	3.0	2.4
Developed	4.3	6.3	5.8	4.4	7.4	7.8	5.7	8.9	7.3
Developing	1.8	1.9	2.4	1.8	2.1	2.9	2.9	3.3	3.7
World	2.5	3.1	3.2	2.5	3.5	4.0	3.7	4.9	4.5

Source: IIASA WFS simulations, May 2009.

In the TAR-V1 scenario, with a high demand for first-generation biofuels due to high national targets and only gradual introduction of second-generation technologies, agricultural value added increases substantially, by some 6.6 percent globally by 2030. Global agricultural value added increases by USD 73 billion in 2020, USD 120 billion in 2030 and USD 155 billion in 2050, in 1990 dollars. Again, the percentage gains in TAR-V1 are higher for developed countries (averaging about 6.9 percent in 2020) than developing regions (3.4 percent), where estimated gains fall in a range of 1.7 to 5.7 percent. For developed countries, the TAR-V1 scenario estimates the increases in agricultural value added (in 1990 dollars) resulting from biofuel development at USD 33 billion in 2020 and USD 62 billion in 2030. The corresponding values for developing countries are USD 37 billion in 2020 and USD 51 billion in 2030.

Impacts on the use of cultivated land

Discussion of the extent and kind of land required for biofuel production and of the impacts on cultivated land caused by expanding biofuel production distinguishes two elements: estimating direct land-use change from the extent of land used for producing biofuel feedstocks; and estimating the indirect land-use effects that can result from bioenergy production displacing services or commodities (food, fodder, fibre products) from arable land currently in production.

This study applies a general equilibrium framework that can capture both direct and indirect land-use changes by modelling the responses of consumers and producers to price changes induced by introducing competition with biofuel feedstock production. This approach accounts for land-use changes while also considering production intensification on existing agricultural land and consumer responses to changing availability and prices of agricultural commodities.

In a baseline projection without any use of agricultural feedstocks for biofuel production, as portrayed in the FAO-REF-00 scenario, the expansion of arable land to meet growing food and feed requirements between 2000 and 2020 amounts to about 80 million ha. Africa and Latin America, with projected increases in cultivated land of 39 and 33 million ha respectively, account for more than 85 percent of total net arable land expansion.

Table 3.31
Impacts of biofuel expansion on cultivated land use

	Change in cultivated land relative to reference scenario FAO-REF-00 *(%)*								
	World			Developed countries			Developing countries		
Scenario	2020	2030	2050	2020	2030	2050	2020	2030	2050
FAO-REF-01	8	8	5	3	3	1	5	5	4
WEO-V1	19	19	21	6	6	5	12	13	16
WEO-V2	20	23	29	6	8	7	13	15	21
TAR-V1	38	46	48	12	14	11	24	30	36
TAR-V3	29	30	29	9	9	6	19	20	22

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Table 3.31 shows the additional use of cultivated land in 2020, 2030 and 2050 in comparison with a scenario without any crop-based biofuels. For the WEO and TAR biofuel scenarios shown, this additional use in 2020 falls in the range of 19 million ha (WEO-V1) to 38 million ha (TAR-V1). For developed countries, the arable land-use increases in different biofuel scenarios during 2000 to 2020 are in the range of 6 to 12 million ha, compared with a net decrease of 3 million ha in a scenario without biofuels. In the baseline without biofuels (FAO-REF-00), the increase in arable land use between 2000 and 2020 amounts to 87 million ha; for comparison, additional crop demand with biofuel development results in a total expansion of cultivated land use of 99 to 112 million ha, and additional use of 12 to 24 million ha. The difference of 24 million ha of arable land use in developing countries in the TAR-V1 scenario (compared with results without biofuel demand) is mainly explained by additional expansions of 9 million ha in sub-Saharan Africa and 11 million ha in South America.

When looking at differences in the expansion of cultivated land for the period 2000 to 2030, the range of estimates for biofuel scenarios widens further, from an additional 19 million ha (WEO-V1) to 46 million ha (TAR-V1).

Across the full range of simulated scenarios (including SNS scenarios), the use of cultivated land in 2020 ranges from 1 643 to 1 691 million ha, a difference of 48 million ha. In 2030, it ranges from 1 676 to 1 734 million ha, representing a maximum additional use of 58 million ha.

Increases of harvested area (Table 3.32) account for both the expansion of cultivated land and increased multicropping, i.e., the intensification of cropping on existing cultivated land. For the WEO and TAR biofuel scenarios this additional harvested area falls in the range of 26 million ha (WEO-V1) to 59 million ha (TAR-V1). Under different scenarios, the harvested area in developed countries increases by 10 to 18 million ha, and in developing countries by 17 to 35 million ha. While Africa and South America account for more than 80 percent of physical land expansion (additional cultivated land), their combined share in additional harvested area is only about 45 percent, which indicates that higher agricultural prices lead to a substantial intensification of cropping also in regions with limited land resources.

Table 3.32
Impacts of biofuel expansion on harvested area

	Change relative to reference scenario FAO-REF-00 *(%)*								
	World			Developed countries			Developing countries		
Scenario	2020	2030	2050	2020	2030	2050	2020	2030	2050
FAO-REF-01	13	15	8	6	7	2	7	8	6
WEO-V1	29	33	31	10	13	6	19	20	25
WEO-V2	30	39	43	10	15	8	20	24	34
TAR-V1	57	74	71	17	23	12	38	49	57
TAR-V3	45	50	42	14	17	7	30	32	35

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

In summary, while total global arable land use is only 1 to 3 percent higher in biofuel scenarios than in a situation without biofuels, the impact becomes substantial when expressed in terms of net cultivated land expansion during 2000 to 2020, 2000 to 2030, and 2000 to 2050. From this perspective, the impact of biofuel scenarios is to increase the net expansion of cultivated land by 20 to 45 percent in 2000 to 2020, 15 to 40 percent in 2000 to 2030, and 12 to 30 percent in 2000 to 2050.

Second-generation biofuels

The previous section demonstrated that concerns about expanding the use of first-generation biofuels, especially those derived from cereals and oilseeds, are well justified in view of their possible impacts on agricultural prices, food security and land use.

In this context, second-generation biofuels, produced from woody or herbaceous non-food plant materials as feedstocks, have attracted great attention and raised hopes that the substantial technological and economic barriers that still hamper the commercial deployment of second-generation technologies can soon be resolved, to allow their use and full commercialization in the near future.

Some of the problems associated with first-generation biofuels can be avoided by the production of biofuels using agricultural and forest residues and non-food crop feedstocks. First, the energy yields per hectare achievable with second-generation feedstocks are generally higher than those of first-generation biofuels; and second, land of different quality could possibly be used for their production, thus limiting or avoiding land-use competition with food production, as lignocellulosic feedstocks are expected to be grown mainly outside cultivated land.

Following recent substantial government grants for the development of second-generation feedstocks and conversion technologies, and based on the announced plans of companies developing second-generation biofuel facilities, an optimistic view is that fully commercial-scale operations could possibly be seen as early as 2012. However, with the complexity of the technical and economic challenges involved, a more realistic expectation is that wide deployment of commercial plants is unlikely to begin before 2015 or 2020. Therefore it is still uncertain what contribution second-generation biofuels will make to meeting the global transport fuel demand by 2030 (IEA, 2008a).

Uncertainties have been included in the scenario analysis by simulating the outcomes for a range of assumptions about the expected share of biofuels that will be contributed by second-generation fuels (Table 3.33).

A recent report published by IEA states that both principal conversion processes – bio-geochemical conversion of cellulose to ethanol and thermo-chemical conversion to FT-diesel – can potentially convert 1 dry tonne of biomass (with about 20 GJ/tonne energy content) to about 6.5 GJ of energy in the form of biofuels, representing an overall biomass-to-biofuel conversion efficiency of about 35 percent (IEA, 2008a). Ranges of indicative biofuel yields per dry tonne of biomass are shown in Table 3.34.

Table 3.33
Shares and total amounts of second-generation biofuels

	Share in total transport biofuels *(%)*			Use *(million TOE)*		
Scenario	2020	2030	2050	2020	2030	2050
Global average						
WEO-V1	3	13	30	3	17	62
WEO-V2	0	0	10	0	0	21
WEO-V3	13	30	49	13	38	103
TAR-V1	2	12	26	5	37	110
TAR-V2	0	0	10	0	0	42
TAR-V3	22	38	55	41	113	234
Developed countries						
WEO-V1	4	19	40	3	15	50
WEO-V2	0	0	10	0	0	12
WEO-V3	18	36	59	11	29	73
TAR-V1	4	18	39	5	32	84
TAR-V2	0	0	10	0	0	21
TAR-V3	33	51	68	39	91	146

Source: Fischer *et al.*, 2009.

Table 3.34
Indicative biofuel yields of second-generation conversion technologies

	Biofuel yield *(litres/dry tonne)*		Energy content *(MJ/litre)*	Energy yield *(GJ/dry tonne)*		Biomass input *(dry tonne/TOE)*	
Process	Low	High	LHV	Low	High	Low	High
Biochemical enzymatic hydrolysis ethanol	110	300	21.1	2.3	6.3	18.0	6.6
Thermo-chemical FT-diesel	75	200	34.4	2.6	6.9	16.2	6.1
Syngas-to-ethanol	120	160	21.1	2.5	3.4	16.5	12.4

Source: IEA, 2008a.

Assuming that average biochemical ethanol yields of 250 litres per dry tonne of biomass will be achievable in 2020 and 300 litres in 2030, and that thermo-chemical FT-diesel conversion will produce 160 litres per dry tonne of biomass in 2020 and 200 litres in 2030, each tonne of oil equivalent of second-generation biofuels will require an average of 7.7 dry tonnes of biomass in 2020, 6.4 dry tonnes by 2030, and 6 dry tonnes in 2050. This results in the biomass demands for second-generation biofuels shown in Table 3.35.

Table 3.35
Biomass demand for second-generation biofuels

	Global demand			Demand in developed countries		
	(million dry tonnes)					
Scenario	2020	2030	2050	2020	2030	2050
WEO-V1	19	106	370	19	95	300
WEO-V2	0	0	125	0	0	74
WEO-V3	97	240	615	87	186	440
TAR-V1	35	234	660	35	207	500
TAR-V2	0	0	254	0	0	128
TAR-V3	315	725	1 402	297	583	875

Source: Fischer *et al.*, 2009.

Rapid deployment of second-generation conversion technologies after 2015 to meet the biofuel production of the TAR-V3 scenario in 2020 and 2030 would require some 315 million dry tonnes of biomass in 2020, increasing to 725 million dry tonnes in 2030. Of these, about 300 million dry tonnes in 2020 and nearly 600 million dry tonnes in 2030 would be required to meet the demand in developed countries.

Land required for second-generation biofuels

Low-cost crop and forest residues, wood process wastes and the organic fraction of municipal solid wastes can all be used as lignocellulosic feedstocks. In some regions, substantial volumes of these materials are available and may be used. In such cases, the production of biofuels requires well-designed logistics systems but no additional land. In other regions, with limited residues and suitable wastes and where large and growing amounts of feedstocks are demanded, additional land will be needed for plantations of perennial energy grasses or short-rotation forest crops. Typical yields for the most important suitable feedstocks are summarized in Table 3.36.

Taking an average typical yield of about 10 dry tonnes per hectare as possible and reasonable in 2020, the biomass requirements listed in Table 3.35, with a maximum of 315 million dry tonnes in 2020, imply that up to 32 million ha of land will be needed if all biomass is to come from plantations. In reality, the land requirement in 2020 will be much lower, owing to the availability of large amounts of cheap crop and forest residues. In this early stage of second-generation biofuel development, most of the biomass will be required in developed countries.

By 2030, assuming that research and experience increase average yields to about 15 dry tonnes per hectare (as suggested in Table 3.36), the upper limits of land required for feedstock production will be 50 million ha in the TAR-V3 scenario and less than 20 million ha in both the WEO-V3 and the TAR-V1 scenarios.

Table 3.36
Typical yields of second-generation biofuel feedstocks[a]

Feedstock	Current yields (dry tonnes/ha)	Expected yield by 2030 (dry tonnes/ha)
Miscanthus	10	20
Switchgrass	12	16
Short-rotation willow	10	15
Short-rotation poplar	9	13

[a] These yields refer to generally good land; under marginal conditions, yields can be substantially lower.

Source: Worldwatch Institute, 2007.

While the conventional agricultural feedstocks currently used in first-generation biofuel production compete with food crops, second-generation lignocellulose technologies promise substantial greenhouse gas savings and may allow the use of land resources currently not or only extensively used. Acknowledging these significant advantages of second-generation lignocellulosic biofuel feedstocks over conventional agricultural feedstocks, the study employed a detailed geographical resource database (Fischer *et al.*, 2008) to estimate the land potentially available for bioenergy production under a food and environment first paradigm, i.e., excluding land currently used for food and feed production, as well as forests.

This estimation was based on a 5′ by 5′ latitude/longitude grid (of about 10 km by 10 km at the equator). It started from total land area and subtracted all land indicated as artificial and built-up surfaces, all cultivated land and current forest land. The next step was to exclude all areas indicated or designated as legally protected, and then land with very low productivity owing to cold temperatures at high latitudes or altitudes, low annual precipitation, or steep sloping conditions.

Starting with a total global land area of 13.2 billion ha (excluding Antarctica and Greenland) and subtracting all current cultivated land, forests, built-up land, water bodies and non-vegetated land (desert, rocks, etc.) resulted in 4.6 billion ha of land remaining (about 35 percent of the total). When unproductive, marginally productive (e.g., tundra, arid land) and steeply sloped land was excluded, the remaining area was estimated at 1.75 billion ha (Table 3.37), comprising grassland and woodland.

More than two-thirds of this grassland and woodland potentially suitable for biofuel feedstock production is located in developing countries, especially in Africa and South America (Table 3.37). These estimates are indicative only and are subject to the limitations and accuracy of global land cover, soil and terrain data.

Table 3.37
Regional balance of land classified as unprotected grassland and woodland potentially usable for rainfed lignocellulosic biofuel feedstock production

Region	Total grassland and woodland *(million ha)*	Of which *(million ha)*			Potential rainfed yield *(dry tonnes/ha)*		
		Protected areas	Unproductive or marginally productive	Balance	Average yield	Low yield	High yield
North America	659	103	391	165	9.3	6.7	21.4
Europe and Russian Federation	902	76	618	208	7.7	6.9	14.5
Pacific OECD	515	7	332	175	9.8	6.5	20.0
Africa	1 086	146	386	554	13.9	6.7	21.1
East Asia	379	66	254	60	8.9	6.4	19.0
South Asia	177	26	81	71	16.7	7.6	21.5
Latin America	765	54	211	500	15.6	7.1	21.8
Near East and North Africa	107	2	93	12	6.9	6.3	10.6
Developed	2 076	186	1 342	548	8.9	6.7	21.0
Developing	2 530	295	1 029	1 206	14.5	6.8	21.5
World	4 605	481	2 371	1 754	12.5	6.8	21.5

Source: Fischer *et a*l., 2008.

An important current use of these land resources is livestock grazing. Based on UN FAOSTAT data on feed utilization of crops and processed crop products (e.g., oilseed cakes and meals), fodder crop production, national livestock numbers and livestock production, the feed energy provided by each source was estimated for each country to determine the energy gap to be filled by grassland and pastures. The results of detailed livestock feed energy balances suggest that in 2000 about 55 to 60 percent of available grassland biomass globally was required for animal feeding. The shares are about 40 percent in developed countries and an average 65 percent for developing countries, ranging from more than 80 percent in Asian regions to about 50 percent in sub-Saharan Africa.

Hence, at current use levels, the land potentially available for bioenergy production (assuming unbiased distribution between livestock feeding and bioenergy uses) was estimated at about 700 to 800 million ha, characterized by a rather wide range of productivity levels. Of this, an estimated 330 million ha is in developed countries: about one-third each in North America; Europe, the Russian Federation and Central Asian republics; and Pacific OECD. About 450 million ha is in developing countries: 275 million ha in Africa and 160 million ha in Latin America. Regional details of the estimated land areas and potential yields of second-generation lignocellulosic feedstocks are presented in Table 3.37.

Only the demand for livestock feeding was subtracted, as it is currently the main alternative use. No allowances were included for other social or environmental land functions, such as providing a feed source for wildlife. Estimates are also subject to uncertainties regarding grass and pasture yields, which – owing to the scarcity of data – had to be estimated in model simulations with the IIASA/FAO Global AEZ Study (GAEZ) model (Fischer *et al.*, 2008).

It can be concluded that land demand for producing second-generation feedstocks as required for the most demanding TAR-V3 scenario in 2020 (about 30 million ha) and 2030 (about 50 million ha) could be met without having to compete for cultivated land. The results of the TAR scenario with accelerated second-generation biofuel deployment indicate that production of lignocellulosic feedstocks on some 100 million ha would be sufficient to achieve the target biofuel share in world transport fuels in 2050.

However, there is still need to assess and respect the current uses and functions of potentially suitable land and to regulate land use in an integrated approach across sectors, to achieve land-use efficiency, avoid conflicts and protect the rights of the weakest members of society when landownership is uncertain. Another major challenge is developing the massive infrastructure and logistics systems required for second-generation feedstock supply systems.

Combined impacts of climate change and expansion of biofuel production on world food system indicators

The previous sections reviewed the individual impacts of climate change and the expansion of biofuel production on world food system indicators. This section summarizes the results for the combined impacts of both factors, by comparing scenario outcomes with a reference simulation assuming current climate conditions and no use of crops for transport biofuel production.

Agricultural prices

Table 3.38 presents the results of scenario analysis and the deviations of price indices for cereals, all crops and agriculture (all crop and livestock sectors), for a selection of scenarios constructed by combining different climate change projections and assumptions concerning CO_2 fertilization with a range of biofuel expansion scenarios.

Table 3.38
Combined impacts of climate change and biofuel expansion on agricultural prices

Scenario	CO_2 fertilization	Change in price index relative to reference scenario FAO-REF-00 *(%)* 2020	2030	2050	2080
Cereals					
Hadley A2, FAO-REF-01	with	4	5	5	28
Hadley A2, WEO-V1	with	15	13	16	42
Hadley A2, WEO-V2	with	18	18	26	49
Hadley A2, TAR-V1	with	42	41	36	61
Hadley A2, TAR-V3	with	23	20	16	43
CSIRO A2, REF-01	with	9	10	10	28
CSIRO A2, WEO-V1	with	22	17	20	43
CSIRO A2, WEO-V2	with	24	23	30	49
CSIRO A2, TAR-V1	with	49	49	40	61
CSIRO A2, TAR-V3	with	29	26	20	45
Hadley A2, REF-01	without	10	13	16	52
Hadley A2, WEO-V1	without	20	21	30	68
Hadley A2, WEO-V2	without	24	26	42	79
Hadley A2, TAR-V1	without	49	54	53	87
Hadley A2, TAR-V3	without	25	29	31	70
Crops					
Hadley A2, REF-01	with	2	3	2	15
Hadley A2, WEO-V1	with	13	11	12	25
Hadley A2, WEO-V2	with	14	13	17	28
Hadley A2, TAR-V1	with	36	35	31	41
Hadley A2, TAR-V3	with	24	19	15	28
CSIRO A2, REF-01	with	6	6	5	14
CSIRO A2, WEO-V1	with	17	13	15	24
CSIRO A2, WEO-V2	with	18	16	20	27
CSIRO A2, TAR-V1	with	42	40	34	40
CSIRO A2, TAR-V3	with	28	23	18	27
Hadley A2, REF-01	without	7	9	12	33
Hadley A2, WEO-V1	without	17	18	24	44
Hadley A2, WEO-V2	without	19	20	30	48
Hadley A2, TAR-V1	without	44	45	45	61
Hadley A2, TAR-V3	without	28	28	27	48
Agriculture					
Hadley A2, REF-01	with	1	2	1	11
Hadley A2, WEO-V1	with	9	7	8	17
Hadley A2, WEO-V2	with	10	9	12	19
Hadley A2, TAR-V1	with	27	25	22	27
Hadley A2, TAR-V3	with	17	13	10	19
CSIRO A2, REF-01	with	4	4	4	10
CSIRO A2, WEO-V1	with	13	9	11	17
CSIRO A2, WEO-V2	with	13	12	15	19
CSIRO A2, TAR-V1	with	32	30	24	27
CSIRO A2, TAR-V3	with	21	17	12	18
Hadley A2, REF-01	without	5	7	9	23
Hadley A2, WEO-V1	without	13	13	17	31
Hadley A2, WEO-V2	without	14	15	22	34
Hadley A2, TAR-V1	without	33	33	33	42
Hadley A2, TAR-V3	without	20	20	19	33

Sources: IIASA WFS simulations; reference scenario FAO-REF-00, May 2009.

Comparing these results with outcomes in Table 3.15 (climate change impacts) and Table 3.27 (biofuel expansion impacts) indicates that the effects of both factors will combine to increase agricultural prices. For the next few decades, the most important scenario factor in determining price increases is the scale of crop use as biofuel feedstocks. In the medium and long terms, climate change becomes the overriding factor.

Taking the effects of CO_2 fertilization on crop yields into account, the simulated cereal price increases for the presented scenario combinations up to 2050 range from 15 to 40 percent when using the HadCM3 climate model outputs, and are somewhat higher when applying climate scenarios based on the CSIRO GCM. Without CO_2 fertilization effects, the cereal price increases for the decades up to 2050 range from 20 to 55 percent. Simulation results for the 2080s, when climate change impacts seriously affect crop yields, the calculated cereal price increases range from 40 to 60 percent with CO_2 fertilization and from 70 to 90 percent without CO_2 fertilization.

Cereal production and consumption

Table 3.39 lists the scenario results regarding production increases relative to the baseline scenario FAO-REF-00 (without climate change and with no crop use for biofuel production).

Table 3.39
Combined impacts of climate change and biofuel expansion on cereal production

Scenario	CO_2 fertilization	Change relative to reference scenario FAO-REF-00 *(million tonnes)*			
		2020	2030	2050	2080
Hadley A2, REF-01	with	70	65	54	-26
Hadley A2, WEO-V1	with	148	160	184	122
Hadley A2, WEO-V2	with	149	197	273	219
Hadley A2, TAR-V1	with	237	320	311	278
Hadley A2, TAR-V3	with	181	209	198	142
CSIRO A2, REF-01	with	55	48	31	-16
CSIRO A2, WEO-V1	with	126	146	161	126
CSIRO A2, WEO-V2	with	133	180	250	228
CSIRO A2, TAR-V1	with	222	299	291	291
CSIRO A2, TAR-V3	with	165	190	177	151
Hadley A2, REF-01	without	56	45	16	-98
Hadley A2, WEO-V1	without	135	138	139	41
Hadley A2, WEO-V2	without	137	176	224	144
Hadley A2, TAR-V1	without	223	294	266	193
Hadley A2, TAR-V3	without	179	183	153	66

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Table 3.40
Combined impacts of climate change and biofuel expansion on cereal consumption (excluding biofuel use)

Scenario	CO_2 fertilization	Change (excluding biofuel feedstocks) relative to reference scenario FAO-REF-00 *(million tonnes)* 2020	2030	2050	2080
Hadley A2, REF-01	with	-10	-21	-25	-100
Hadley A2, WEO-V1	with	-33	-47	-60	-117
Hadley A2, WEO-V2	with	-43	-63	-99	-144
Hadley A2, TAR-V1	with	-88	-122	-128	-156
Hadley A2, TAR-V3	with	-53	-65	-61	-111
CSIRO A2, REF-01	with	-24	-38	-43	-92
CSIRO A2, WEO-V1	with	-51	-60	-78	-111
CSIRO A2, WEO-V2	with	-57	-78	-118	-133
CSIRO A2, TAR-V1	with	-102	-142	-149	-144
CSIRO A2, TAR-V3	with	-66	-83	-80	-104
Hadley A2, REF-01	without	-24	-41	-63	-170
Hadley A2, WEO-V1	without	-49	-68	-104	-191
Hadley A2, WEO-V2	without	-57	-82	-144	-221
Hadley A2, TAR-V1	without	-102	-148	-174	-232
Hadley A2, TAR-V3	without	-60	-86	-105	-183

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Comparing these scenario results with the information in Table 3.40 indicates that up to 2050 there is relatively little climate change impact on aggregate cereal supply and consumption under the HadCM3 scenario with CO_2 fertilization; with CSIRO GCM-derived climate change impacts, the shortfall in consumption increases by about 20 million tonnes compared with biofuels only. Without CO_2 fertilization effects on crop yields, the decrease in consumption for HadCM3 in 2030 is 68 to 148 million tonnes, of which about 25 million tonnes is due to climate change. In 2050, the consumption reduction is in the range of 104 to 174 million tonnes, of which about 50 million tonnes is caused by climate change. In the long term, looking at results for 2080, climate change accounts for up to two-thirds of the reduction in cereal consumption in scenarios with CO_2 fertilization and for up to 85 percent in the HadCM3 scenario without CO_2 fertilization.

Risk of hunger

Combined scenario results regarding the number of people at risk of hunger are shown in Table 3.41. Results are consistent with the previous discussion on price changes and cereal consumption impacts. Again, the conditions portrayed by the FAO reference projections (FAO, 2006) imply a vast improvement in reducing undernourishment. Therefore, relative changes compared with the baseline FAO-REF-00 are large in 2050 and 2080 but relatively small in absolute terms.

Table 3.41
Combined impacts of climate change and biofuel expansion on risk of hunger indicator

Scenario	CO_2 fertilization	Change in number of people at risk of hunger relative to reference scenario FAO-REF-00 *(million people)*			
		2020	2030	2050	2080
Hadley A2, REF-01	with	6	9	2	29
Hadley A2, WEO-V1	with	51	41	34	39
Hadley A2, WEO-V2	with	59	54	54	43
Hadley A2, TAR-V1	with	150	148	99	55
Hadley A2, TAR-V3	with	100	82	39	40
CSIRO A2, REF-01	with	14	23	4	21
CSIRO A2, WEO-V1	with	14	23	4	32
CSIRO A2, WEO-V2	with	82	75	60	35
CSIRO A2, TAR-V1	with	178	176	104	48
CSIRO A2, TAR-V3	with	123	108	46	32
Hadley A2, REF-01	without	33	43	41	58
Hadley A2, WEO-V1	without	75	76	78	70
Hadley A2, WEO-V2	without	85	88	102	77
Hadley A2, TAR-V1	without	179	192	153	87
Hadley A2, TAR-V3	without	117	119	88	72

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Cultivated land

Tables 3.42 and 3.43 present the combined impacts of climate change and biofuel expansion scenarios on cultivated land use. Summarizing over all the scenarios shown in Table 3.42, the additional use of cultivated land falls by 16 to 40 million ha in 2020, 17 to 49 million ha in 2030, and 20 to 58 million ha in 2050.

For harvested area, shown in Table 3.43, the additional use ranges from 24 to 59 million ha in 2020, 28 to 78 million ha in 2030, and 28 to 85 million ha in 2050.

Conclusions

This paper reports on a large number of scenario experiments conducted to improve the understanding of how climate change and expanding bioenergy use may alter the long-term outlook for food, agriculture and resource availability.

IIASA's global and spatial agro-ecological and socio-economic assessment framework provided the analytical means and science-based knowledge for the assessment. The following is a summary of the main conclusions and implications derived from the global quantitative analysis:

Table 3.42
Combined impacts of climate change and biofuel expansion on use of cultivated land

Scenario	CO_2 fertilization	Change relative to reference scenario FAO-REF-00 *(million ha)*			
		2020	2030	2050	2080
Hadley A2, REF-01	with	4	5	3	16
Hadley A2, WEO-V1	with	16	17	20	33
Hadley A2, WEO-V2	with	17	20	26	39
Hadley A2, TAR-V1	with	35	43	47	59
Hadley A2, TAR-V3	with	26	27	27	39
CSIRO A2, REF-01	with	8	11	10	20
CSIRO A2, WEO-V1	with	20	21	26	37
CSIRO A2, WEO-V2	with	21	25	33	43
CSIRO A2, TAR-V1	with	40	48	53	63
CSIRO A2, TAR-V3	with	30	33	33	44
Hadley A2, REF-01	without	8	12	14	33
Hadley A2, WEO-V1	without	19	22	31	50
Hadley A2, WEO-V2	without	20	25	37	56
Hadley A2, TAR-V1	without	39	49	58	75
Hadley A2, TAR-V3	without	29	33	38	57

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

Table 3.43
Combined impacts of climate change and biofuel expansion on harvested area

Scenario	CO_2 fertilization	Change relative to reference scenario FAO-REF-00 *(million ha)*			
		2020	2030	2050	2080
Hadley A2, REF-01	with	7	9	3	22
Hadley A2, WEO-V1	with	24	28	28	47
Hadley A2, WEO-V2	with	25	33	38	56
Hadley A2, TAR-V1	with	51	68	67	86
Hadley A2, TAR-V3	with	39	45	38	56
CSIRO A2, REF-01	with	13	17	11	24
CSIRO A2, WEO-V1	with	30	36	34	50
CSIRO A2, WEO-V2	with	31	41	45	58
CSIRO A2, TAR-V1	with	58	75	74	89
CSIRO A2, TAR-V3	with	46	52	45	60
Hadley A2, REF-01	without	14	19	20	49
Hadley A2, WEO-V1	without	30	38	46	75
Hadley A2, WEO-V2	without	32	43	56	84
Hadley A2, TAR-V1	without	59	78	85	112
Hadley A2, TAR-V3	without	45	55	56	85

Sources: IIASA WFS simulations; FAO-REF-00 scenario, May 2009.

- At the global aggregate level, climate change projected by different GCMs causes only modest changes to world food system indicators (prices, cereal production, food consumption, cultivated land use) in the period up to 2050.
- These findings assume full agronomic adaptation by farmers and do not take into account climate variability, which is expected to increase over the coming decades and may be an important destabilizing factor in the short to medium term.
- The capacity to adapt to climate change impacts is strongly linked to future development paths. The socio-economic and, even more so, the technological characteristics of different development futures strongly affect societies' capability to adapt to and mitigate climate change.
- Assumptions regarding yield increases due to increased atmospheric CO_2 concentrations (the CO_2 fertilization effect) play an important role in scenario outcomes. When disregarding these effects, negative climate change impacts on crop yields and world food system indicators become noticeable even in the short term, and are very substantial in the medium and long terms.
- Scenario results confirm that, with and without CO_2 fertilization, the impacts of climate change on crop yields and production could become severe in the second half of this century.
- If expansion of biofuel production continues to rely mainly on agricultural crops, and if expansion follows the pace projected by IEA in 2008 or achieves the levels implied by mandates and targets set in many countries, this additional non-food use of crops will have a significant impact on the world food system.
- While biofuels could have an especially large impact in the period up to 2030, the aggregate impact on the food system is likely to decrease over time. The opposite is to be expected for climate change impacts.
- For the range of scenarios analysed in this assessment, the combined impact of climate change and biofuel expansion on aggregate crop prices is in the range of a 10 to 45 percent increase. Decrease of cereal consumption typically falls initially within 35 to 100 million tonnes, increasing to a range of 60 to 150 million tonnes by 2050. Regarding cultivated land, additional use in the range of 20 to 50 million ha by 2030 and 25 to 60 million ha in 2050 can be expected.

References

Bruinsma, J., ed. 2003. *World agriculture: Towards 2015/30, an FAO perspective*. London, Earthscan and Rome, FAO. www.fao.org/es/esd/gstudies.htm.

FAO. 2001. *The State of Food Insecurity in the World 2001*. Rome.

FAO. 2006. *World agriculture: towards 2030/2050 – Interim report*. Rome. www.fao.org/es/esd/at2050web.pdf.

FAO. 2008a. *The State of Food and Agriculture. Biofuels: prospects, risks and opportunities*. Rome. 138 pp.

FAO. 2008b. *The State of Food Insecurity in the World 2008*. Rome.

FAOSTAT. Time-series and cross-sectional data relating to food and agriculture. http://faostat.fao.org/default.aspx.

Fischer, G., Shah. M. & van Velthuizen, H. 2002. *Climate change and agricultural vulnerability*. Special report for the World Summit on Sustainable Development, Johannesburg 2002. Laxenburg, Austria, IIASA. 152 pp.

Fischer, G., Frohberg, K., Keyzer, M.A. & Parikh, K.S. 1988. *Linked national models: a tool for international policy analysis*. Berlin, Kluwer Academic Publishers. 214 pp.

Fischer, G., Frohberg, K., Parry, M.L. & Rosenzweig, C. 1994. Climate change and world food supply, demand and trade: Who benefits, who loses? *Global Environmental Change*, 4(1): 7–23.

Fischer G., van Velthuizen, H., Shah, M. & Nachtergaele, F.O. 2002. *Global agro-ecological assessment for agriculture in the 21st century: Methodology and results.* IIASA RR-02-02. Laxenburg, Austria, IIASA.

Fischer, G., Shah, M., Tubiello, F.N. & van Velhuizen, H. 2005. *S*ocio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Phil. Trans. Royal Soc. B.*

Fischer, G., Nachtergaele, F., Prieler, S., Teixeira, E., van Velthuizen, H.T., Verelst, L. & Wiberg, D. 2008. *Global agro-ecological zones assessment for agriculture (GAEZ 2008)*. Laxenburg, Austria, IIASA, and Rome, FAO.

Fischer, G., Teixeira, E., Tothne-Hizsnyik, E. & van Velthuizen, H. 2009. Land use dynamics and sugarcane production. *In* P. Zuurbier and J. van de Vooren, eds. *Sugarcane ethanol, Contributions to climate change mitigation and the environment.* Wageningen, Netherlands, Wageningen Academic Publishers, and Laxenburg, Austria, IIASA.

Gordon, H.B. & O'Farrell, S.P. 1997. Transient climate change in the CSIRO coupled model with dynamic sea ice. *Monthly Weather Review*, 125(5): 875–907.

Gordon, C., Cooper, C.A. Snr, Banks, H., Gregory, J.M., Johns, T.C., Mitchell, J.F.B. & Wood, R.A. 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics*, 16: 147–168.

Hirst, A.C., Gordon, H.B. & O'Farrell, S.P. 1997. Response of a coupled ocean-atmosphere model including oceanic eddy-induced advection to anthropogenic CO_2 increase. *Geophys. Res. Lett.*, 23(23): 3361–3364.

IEA. 2008a. *From 1st- to 2nd-generation biofuel technologies. An overview of current industry and RD&D activities.* Paris, OECD/IEA. www.iea.org.

IEA. 2008b. *World energy outlook 2008*. Paris, OECD/IEA. 578 pp.

Nakicenovic, N. & Swart, R., eds. 2000. *Special report on emissions scenarios.* Cambridge, UK, Cambridge University Press and IPCC. 570 pp.

New, M., Lister, D., Hulme, M. & Makin, I. 2002. A high-resolution data set of surface climate over global land areas. *Climate Research*, 21.

Pope, V.D., Gallani, M.L., Rowntree, P.R. & Stratton, R.A. 2000. The impact of new physical parametrizations in the Hadley Centre climate model – HadAM3. *Climate Dynamics*, 16: 123–146.

Rosenzweig, C. & Parry, M.L. 1994. Impacts of climate change on world food supply. *Nature*, 367: 133–138.

Tubiello, F.N. & Fischer, G. 2006. Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000–2080. T*echnological Forecasting and Social Change,* doi:10.1016/j.techfore.2006.05.027.

UN. 2009. *World Population Prospects: The 2008 Revision*. New York.

Worldwatch Institute. 2007. *Biofuels for transport. Global potential and implications for sustainable energy and agriculture*. London, Earthscan.

Annex 3.1

The modelling framework

The study is based on a state-of-the-art ecological-economic modelling approach. The scenario-based quantified findings of the study rely on a modelling framework that includes the FAO/IIASA Agro-Ecological Zone (AEZ) model and the IIASA World Food System (WFS) model as components. The modelling framework encompasses climate scenarios, agro-ecological zoning information, demographic and socio-economic drivers, and production, consumption and world food trade dynamics.

AEZ methodology

The AEZ modelling uses detailed agronomic-based knowledge to simulate land resources availability, assess farm-level management options and estimate crop production potentials. It employs detailed spatial biophysical and socio-economic datasets to distribute its computations at fine-gridded intervals over the entire globe (Fischer *et al.*, 2002; 2005). This land resources inventory is used to assess, for specified management conditions and levels of inputs, the suitability of crops under both rainfed and irrigated conditions, and to quantify expected attainable production levels of cropping activities relevant to specific agro-ecological contexts. The characterization of land resources includes components of climate, soils, land form and current land cover. Crop modelling and environmental matching procedures are used to identify crop-specific environmental limitations under various levels of inputs and management conditions.

In summary, the AEZ framework contains the following basic elements:

- land resources database, containing geo-referenced climate, soil and terrain data;
- land utilization types (LUTs) database of agricultural production systems, describing crop-specific environmental requirements and adaptability characteristics, including input levels and management;
- mathematical procedures for matching crop LUT requirements with agro-ecological zones data and estimating potentially attainable crop yields, by land unit and grid-cell; the AEZ global assessment includes 2.2 million land grid cells at 5′ by 5′ latitude/longitude;
- assessments of crop suitability and land productivity;
- applications for agricultural development planning.

WFS model

The WFS model comprises a series of national and regional agricultural economic models. It provides a framework for analysing the world food system and for viewing national food and agricultural components as embedded in national economies and interacting with each other at the international trade level. The model consists of 34 national and regional geographical components covering the world. The individual national/regional models are linked by means of a world market, where international clearing prices are computed to equalize global demand with supply (Box A3.1).

Simulations with the WFS model generate a variety of outputs. At the global level, these include world market prices, global population, global production and global consumption. At the country level, they include producer and retail prices, levels of production, use of primary production factors (land, labour and capital), intermediate input use (feed and fertilizer), human consumption, use for biofuel production, commodity trade, value added in agriculture, investment by sector and income by group and/or sector.

Population growth and technology are key external inputs to the WFS model system. Population numbers and projected incomes are used to determine the demand for food for the period of study. Technology affects yield estimates, by modifying the efficiency of production per given units of inputs and land. For simulations of historical periods up to the present, population data are taken from official UN country-level data, while the rate of technical progress is estimated from past agricultural performance.

To assess agricultural development over the next decades to 2050, it was necessary first to make some coherent assumptions about how key socio-economic drivers of food systems might evolve over that period. For the analysis reported in this chapter, population projections were taken from the UN database for world population prospects (UN, 2009). Economic growth of countries and regional groups in the WFS model were calibrated according to information provided by the World Agriculture Towards 2030/2050 study group at FAO (J. Bruinsma, 2009, personal communication).

Another external input to the WFS model system is projected climate change, which affects region-specific crop suitability and attainable yields. The economic model uses this spatial agronomic information (derived from AEZ) in an aggregate form as an input in allocating land and agricultural inputs (Fischer *et al.*, 2005). In this study, results of the coupled atmosphere-ocean GCM developed by the United Kingdom's Hadley Centre for Climate Prediction and Research and Australia's CSIRO were used to take into account climate change impacts on land suitability and productivity (Fischer, Shah and van Velthuizen, 2002).

Box A3.1 - How does the world food system work?

The WFS model is an applied general equilibrium model system. While focusing on agriculture, this necessitates that all other economic activities are also represented in the model. Financial and commodity flows within a country and at the international level are kept consistent in that they must balance, by imposing a system of budget constraints and market clearing conditions. Whatever is produced will be demanded, for human consumption, feed, biofuel use or as an intermediate input. Alternatively, commodities can be exported or put into storage. Consistency of financial flows is imposed at the level of the economic agents in the model (individual income groups, governments, etc.), nationally and internationally. This implies that total expenditures cannot exceed total income from economic activities and from abroad, in the form of financial transfers, minus savings. On a global scale, no more can be spent than what is earned.

Each individual model component focuses primarily on the agriculture sector, but also includes a simple representation of the entire economy, which is necessary for capturing essential dynamics among capital, labour and land. For the purpose of international linkage, production, consumption and trade of goods and services are aggregated into nine main agricultural sectors: wheat; rice; coarse grains; bovine and ovine meat; dairy products; other meat and fish; oilseed cakes and protein meals; other food; and non-food agriculture. The rest of the economy is coarsely aggregated into one simplified non-agricultural sector. In the model, agricultural commodities may be used for human consumption, feed, biofuel feedstock, intermediate consumption and stock accumulation. Non-agricultural commodities also contribute as investment and as inputs for processing and transporting agricultural goods. All physical and financial accounts are balanced and mutually consistent: production, consumption and financial accounts at the national level; and trade and financial flows at the global level.

Linkage of country and country group models occurs through trade, world market prices and financial flows. The system is solved in annual increments, simultaneously for all countries in each period. Within each one-year period, demand changes with price, and commodity buffer stocks can be adjusted for short-term supply response. Production in the following marketing year is affected by changes in relative prices (owing to time lags in the agricultural production cycle). This feature makes the WFS model a recursively dynamic system.

The market clearing process results in equilibrium prices, i.e., a vector of international prices such that global imports and exports balance for all commodities. These market clearing prices are then used to determine value added in the production and income of households and governments.

Within each regional unit, the supply modules allocate land, labour and capital as functions of the relative profitability of the different crop and livestock sectors. In particular, actual cultivated area is computed from both agro-climatic land parameters (derived from AEZ) and profitability estimates. Once area, labour and capital are assigned to cropping and livestock activities, yields and livestock production are computed as a function of fertilizer applications, feed rates and available technology.

The IIASA WFS model has been calibrated and validated over past time windows, and reproduces regional consumption, production and trade of major agricultural commodities in 2000. Several applications of the model to agricultural policy and climate change impact analysis have been published (e.g., Fischer *et al.*, 1988; 1994; Rosenzweig and Parry, 1994; Fischer, Shah and van Velthuizen, 2002; Fischer *et al.*, 2005; Tubiello and Fischer, 2006).

Annex 3.2

Aggregation of world food system components to world regions

Economic group	Region	WFS component
Developed	North America	Canada, United States
	Europe and Russian Federation	Austria, EU9, Eastern Europe, former Soviet Union, Turkey
	Pacific OECD	Australia, Japan, New Zealand
Developing	Sub-Saharan Africa	Kenya, Nigeria Africa oil exporters Africa medium-income/food exporters Africa low-income/food exporters Africa low-income/food importers
	Latin America	Argentina, Brazil, Mexico Latin America high-income/food exporters Latin America high-income/food importers Latin America medium-income
	Near East and North Africa	Egypt Africa medium-income/food importers Near/Middle East oil exporters Near/Middle East medium- and low-income countries.
	East Asia	China Far East Asia high- and medium-income/food importers
	South and Southeast Asia	India, Pakistan, Indonesia, Thailand Asia low-income countries Far East Asia high- and medium-income/food exporters
Rest of the world	Rest of the world	Rest of the world

Aggregate regional country group models

African oil exporters: Algeria, Angola, Congo, Gabon.

Africa medium-income/food exporters: Ghana, Côte d'Ivoire, Senegal, Cameroon, Mauritius, Zimbabwe.

Africa medium-income/food importers: Morocco, Tunisia, Liberia, Mauritania, Zambia.

Africa low-income/food exporters: Benin, the Gambia, Togo, Ethiopia, Malawi, Mozambique, Uganda, the Sudan.

Africa low-income/food importers: Guinea, Mali, the Niger, Sierra Leone, Burkina Faso, Central African Republic, Chad, Democratic Republic of the Congo, Burundi, Madagascar, Rwanda, Somalia, United Republic of Tanzania.

Latin America high-income/food exporters: Costa Rica, Panama, Cuba, Dominican Republic, Ecuador, Suriname, Uruguay.

Latin America high-income/food importers: Jamaica, Trinidad and Tobago, Chile, Peru, Venezuela.

Latin America medium-income: El Salvador, Guatemala, Honduras, Nicaragua, Colombia, Guyana, Paraguay, Haiti, Plurinational State of Bolivia.

South and Southeast Asia high- and medium-income/food exporters: Malaysia, the Philippines.

Southeast Asia high- and medium-income/food importers: Republic of Korea, Democratic People's Republic of Korea, Lao People's Democratic Republic, Viet Nam, Cambodia.

Asia, low-income: Bangladesh, Myanmar, Nepal, Sri Lanka.

Near/Middle East oil exporters: Libyan Arab Jamahiriya, Islamic Republic of Iran, Iraq, Saudi Arabia, Cyprus, Lebanon, Syrian Arab Republic.

Near/Middle East medium- and low-income: Jordan, Yemen, Afghanistan.

The rest of world aggregate includes both more and less developed countries. Although the aggregate variables are dominated by more developed countries in OECD, these countries are not included in the respective broad regional aggregates, developed and developing.