Expert Meeting on How to Feed the World in 2050
Food and Agriculture Organization of the United Nations
Economic and Social Development Department

World Food and Agriculture to 2030/50:

How do climate change and bioenergy alter the long-term outlook for food, agriculture and resource availability?

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1. INTRODUCTION

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 received increased attention in recent times as a means to mitigate climate change, alleviate global energy concerns and foster rural development. Its perceived importance in these three areas has seen biofuels feature prominently on the international agenda. Nevertheless, the rapid growth of biofuels production has raised many concerns among experts worldwide, in particular with regard to 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 biofuels policies, high crude oil prices, increasing global food import demand, below average harvests in some countries and low levels of world food stocks resulted in sudden and substantial increases in world food prices. The consequences were food riots around the world from Mexico to Haiti to Mauritania to Egypt to Bangladesh. Estimates indicate that high food prices increased the number of food insecure people by about 100 million.

This paper presents an integrated agro-ecological and socio-economic spatial global assessment of the inter-linkages of emerging biofuels developments, food security, and climate change. The explicit purpose is to quantify as to what extent climate change and expansion of biofuel production may alter the long-term outlook for food, agriculture and resource availability developed by the FAO in its Agriculture Toward 2030/50 assessment (Alexandratos, 2009; Bruinsma, 2009; FAO, 2006).

International Institute for Applied Systems Analysis' (IIASA)'s modeling framework and models have been developed to analyze spatially the world food and agriculture system and evaluate the impacts and implications of agricultural policies. The modeling framework has recently been extended and adapted to explicitly incorporate the issues of biofuel development. A brief summary of the methods and models applied in this study is presented below.

2. METHODOLOGY AND DATA

The modeling framework

The analysis is based on a state-of-the-art ecological-economic modeling approach. The scenario-based quantified findings of the study rely on a modeling framework which includes as components, the FAO/IIASA Agro-ecological Zone model (AEZ) and the IIASA world food system model (WFS). The modeling framework encompasses climate scenarios, agro-ecological zoning information, demographic and socio-economic drivers,

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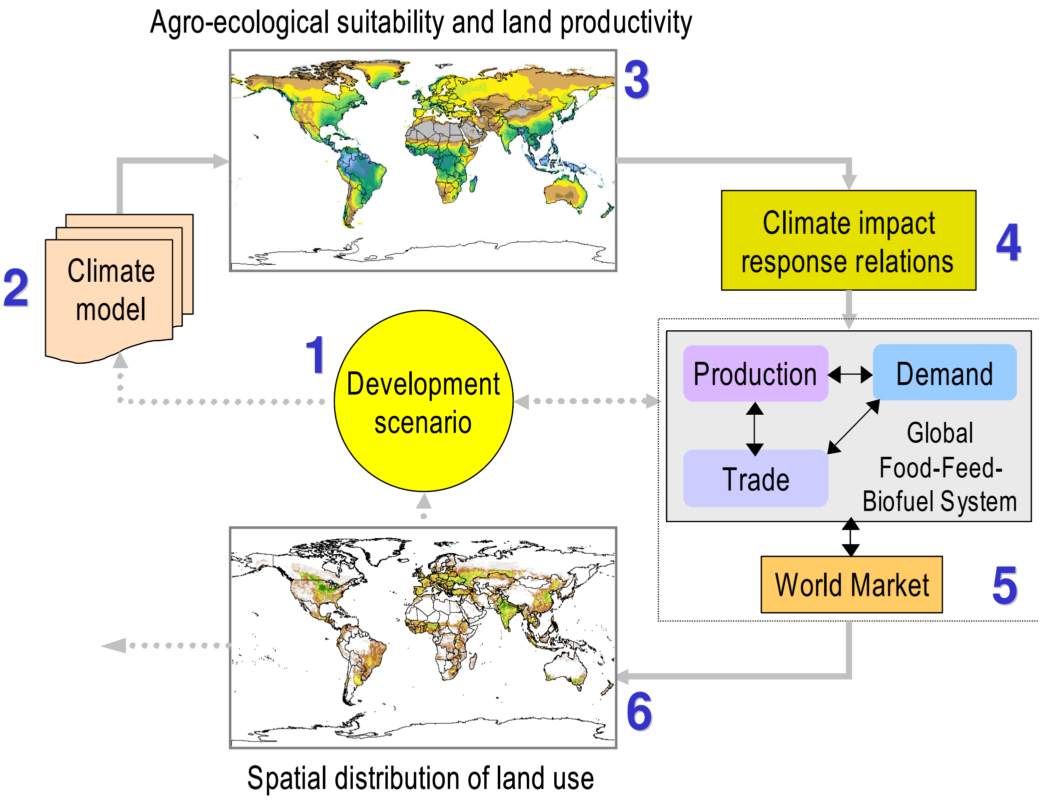
as well as production, consumption and world food trade dynamics (Fischer et al., 2009; Fischer et al., 2005). A summary description of the main model components is provided in Annex 1.

Figure 2.1: Framework for ecological-economic world food system analysis



This modeling framework comprises six main elements, as sketched in Figure 2.1:

1. A storyline and quantified development scenario (usually chosen from the extensive integrated assessment literature) is selected to inform the world food system model of demographic changes in each region and of projected economic growth in the non-agricultural sectors. It also provides assumptions characterizing in broad terms the international setting (e.g. trade liberalization; international migration) and the priorities regarding technological progress. It quantifies selected environmental variables, e.g. greenhouse gas emissions and atmospheric concentrations of CO_2. In this study it also defines scenarios of demand for first- and second-generation biofuels.
2. The emissions pathway associated with the chosen development scenario is used to select among available and matching published outputs of 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.
3. The agro-ecological zones method takes as input a climate scenario and estimates on a spatial grid of 5′ by 5′ latitude/longitude the likely agronomic impacts of climate change and identifies adaptation options.
4. Estimated spatial climate change impacts on yields for all crops are aggregated and incorporated into the parameterization of the national crop production modules of a regionalized world food system model.
5. The global general equilibrium world food system model is used – informed by the development storyline and estimated climate change yield impacts – to evaluate internally consistent world food system scenarios.

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

The evaluation of the potential impacts on production, consumption and trade of agricultural commodities, caused by climate change and/or a rapid expansion of global biofuel use, was carried out in two steps. First, simulations were undertaken representing "futures" where biofuel production was abandoned or frozen at current levels (i.e. of year 2008) and kept constant for the remainder of the simulation period. Second, climate change impacts and alternative levels of biofuel demand, as derived from different energy scenarios, were simulated with the food system model and compared to the respective outcomes without additional biofuels demand or climate change.

The primary role of a reference scenario is to serve as "neutral" point of departure, from which various scenarios take off as variants, with the impact of climate change and/or biofuel expansion being seen in the deviation of these simulation runs from the outcomes of the reference scenario. The simulations were carried out on a yearly basis from 1990 to 2080.

3. BASELINE ASSESSMENT

Before turning to the impacts simulated for different assumptions on biofuel expansion and climate change, we briefly summarize results for a baseline projection. For this neutral point of departure, we have selected scenario FAO-REF-00 (see Table 7.1 in section 7), i.e. a reference projection of the system where no use of agricultural crops as feedstock for biofuel production is assumed and where current climate conditions prevail.

Population increase and economic growth

In the long run, the increase of demand for agricultural products is largely driven by population and economic growth, both foremost in developing countries. Over the next two decades world population growth is projected at about one percent with most of the increase being in developing countries. Population increase is an exogenous input to the model analysis. The most recent available UN population projections (United Nations, 2009) where used as summarized in Table 3.1. Details of regional groupings in the world food system model are shown in Annex 2.

Table 3.1: Population development

	Total population (millions)					
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
North America	306	337	367	392	413	430
Europe & Russia	752	762	766	761	748	729
Pacific OECD	150	153	152	148	142	135
Africa, sub-Saharan	655	842	1056	1281	1509	1723
Latin America	505	574	638	689	725	744
Middle East & N. Africa	303	370	442	511	575	629
Asia, East	1402	1500	1584	1633	1630	1596
Asia, South/Southeast	1765	2056	2328	2553	2723	2839
Rest of World	210	233	249	262	272	280
Developed	1141	1177	1202	1211	1210	1198
Developing	4696	5417	6132	6758	7257	7627
Rest of World[1]	210	233	249	262	272	280
World	6047	6827	7582	8231	8739	9105

Source: United Nations, March 2009.

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[1] The regionalization used in the world food system model is described in Annex 2.

Economic performance in the baseline projection 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 of the FAO perspective study Agriculture Toward 2030/50 based on information provided by the Agriculture Toward 2030/50 study group at FAO (J. Bruinsma, May 2009; personal communication).

Table 3.2: GDP at constant 1990 prices

FAO-REF-01	GDP (billion US $ at constant 1990 prices)					
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
North America	8286	10582	12427	13817	15480	17050
Europe & Russia	7502	9487	11621	14037	16860	19832
Pacific OECD	3795	4304	4781	5173	5534	5888
Africa, sub-Saharan	238	350	531	808	1236	1894
Latin America	1450	2014	2822	4267	6284	8828
Middle East & N. Africa	597	850	1212	1772	2623	3845
Asia, East	1596	4165	8037	13106	18373	24625
Asia, South/Southeast	1255	2020	3136	4840	7293	10139
Rest of World	2418	3000	3640	4343	5103	5913
Developed	19583	24372	28830	33028	37875	42770
Developing	5135	9399	15738	24795	35810	49331
Rest of World	2418	3000	3640	4343	5103	5913
World	27136	36771	48207	62165	78788	98014

Source: IIASA world food system simulations; scenario FAO-REF-00, May 2009.

While the recent economic growth rates of more than 8 percent annually 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 yield and acreage developments. In many developing countries the crop yields for most commodities are lower than those attained in developed countries. At the global level grain yields increased by an average of some 2 percent annually in the period 1970 to 1990 but since then the rate of yield growth has halved.

Table 3.3: Total cereal production and consumption; Baseline simulation without considering climate change and biofuel expansion

FAO-REF-00	Cereal production (million tons)				Cereal consumption (million tons)			
	2000	**2020**	**2030**	**2050**	**2000**	**2020**	**2030**	**2050**
North America	474	588	645	707	304	354	376	404
Europe & Russia	526	552	575	650	545	590	621	684
Pacific OECD	40	48	49	55	46	50	52	52
Africa, sub-Saharan	76	133	172	265	106	179	233	347
Latin America	130	197	221	269	139	196	227	272
Middle East & N. Africa	55	82	94	122	99	148	179	234
Asia, East	423	525	568	636	461	570	620	677
Asia, South/Southeast	345	450	496	573	341	453	494	573
Rest of World	75	94	103	125	103	120	128	146
Developed	1008	1149	1229	1363	858	945	993	1072
Developing	1060	1425	1590	1914	1183	1596	1808	2171
Rest of World	75	94	103	125	103	120	128	146
World	2143	2668	2923	3402	2144	2661	2928	3388

Source: IIASA world food system simulations; scenario FAO-REF-00, May 2009.

With still considerable population growth in the reference projections of scenario FAO-REF-00, total production of cereals increases from 2.1 billion tons in 2000 to 2.9 billion tons in 2030, and further to 3.4 billion tons 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 their share in global consumption increases from 55 percent to 64 percent in this reference projection, net imports of cereals by developing countries are growing over time, from 120 million tons in 2000 to about 220 million tons in 2030, and some 250 million tons by 2050.

Agricultural prices

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

The index of world food prices has increased by some 140 percent during the period 2002 to 2007 primarily a result of increased demand for cereals and oilseeds for biofuels, low world food stocks, reduced harvest in some locations, for example in Australia and Europe due to drought conditions, 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 scenario FAO-REF-00 is characterized by modest increases of world market prices during 2000 to 2050. Table 3.4 shows projected price indexes for crops and livestock products in comparison to 1990 levels for a reference simulation without considering climate change or expansion of biofuel production. In part, this is also the outcome of an assumed further reduction of agricultural support and protection measures.[2]

Table 3.4: Agricultural prices in the Baseline projection, scenario 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

Source: IIASA world food system simulations; scenario FAO-REF-00, May 2009.

Risk of hunger

In 1970, 940 million people in developing countries, a third of the population, were regarded as chronically undernourished. During the next two decades, the number of undernourished people declined by some 120 million to estimated 815 million in 1990. The largest reduction occurred in East Asia where the number of undernourished people declined from some 500 million in 1970 to about 250 million in 1990. The number of undernourished people increased slightly in South Asia and almost doubled in sub-Saharan Africa. The total number of undernourished in the developing countries further declined from 815 million in 1990 to 776 million people in 2000. During this same period, the number of undernourished in sub-Saharan Africa increased from 168 million to 194 million. Africa has the highest proportion of undernourished people, about 35 percent of the total population compared to about 14 percent of the total population of the rest of the developing world.

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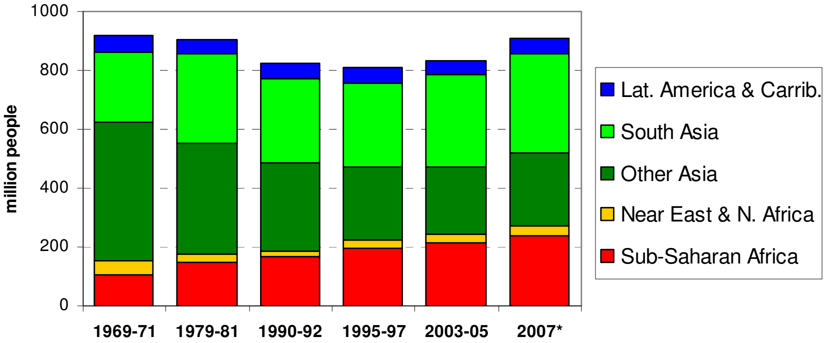
[2] Price dynamics critically depend on assumed long-term rates of technological progress in agriculture. Therefore, the price trends presented here should not be interpreted as a ‘prediction’ of future price development but is rather shown as a characteristic of the chosen reference simulation.

Figure 3.5: Historical trends in number of undernourished people, developing countries



Source: FAO (2008b; 2001).
Note: FAO states the estimate for 2007 is based on partial data for 2006-08 and a simplified methodology and should therefore be regarded as provisional.

The FAO-REF-00 scenario projects a globally decreasing number of people at risk of hunger. The projected decrease is most pronounced in East Asia and South Asia. For Africa a further increase in the number of people at risk of hunger is projected, resulting for 2020 in 35 percent of the total number of people at risk of hunger to originate from Africa, and 40 percent in 2030. While achieving some progress in mitigating hunger, the projected development in this reference scenario FAO-REF-00 is far from being sufficient to meet the reductions necessary to achieve the Millennium Development Goal.

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

FAO-REF-01			Millions			
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Africa, sub-Saharan	196	252	286	271	258	239
Latin America	56	43	31	20	14	10
Middle East & N. Africa	42	51	57	53	52	47
Asia, East	173	139	104	68	42	26
Asia, South/Southeast	364	378	362	278	192	136
Developing countries	833	864	839	691	557	458

Source: IIASA world food system simulations; scenario FAO-REF-00, May 2009.

Value added of crop and livestock production

In the FAO-REF-00 scenario, the global value added of crop and livestock production in 2000 amounts to US1990$ 1260 billion. This is projected to increase by 30 percent in the 20-year period to 2020. In 2030 and 2050 the projected value added amounts to respectively US1990$ 1836 and US1990$ 2192 billion.

Table 3.6: Value added of crop and livestock sector (billion US$ 1990)

FAO-REF-00	Billion US$ 1990					
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
North America	166	179	192	203	214	226
Europe & Russia	206	220	235	245	255	264
Pacific OECD	47	52	57	62	67	71
Africa, sub-Saharan	65	82	105	133	165	198
Latin America	155	190	227	262	289	308
Middle East & N. Africa	55	70	86	104	122	141
Asia, East	249	282	314	342	365	384
Asia, South/Southeast	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	1081	1241	1391	1530
Rest of World	65	71	78	85	93	101
World	1259	1445	1642	1836	2019	2192

Source: IIASA world food system simulations; scenario FAO-REF-00, May 2009.

Cultivated land

Some 1.6 billion ha of land are currently used for crop production, with nearly 1 billion ha under cultivation in the developing countries. During the last 30 years the world's crop area expanded by some 5 million ha annually, with Latin America alone 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.

Projected global use of cultivated land in the FAO-REF-00 baseline scenario increases by about 165 million ha during 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).

Table 3.7: Cultivated land (million hectares)

FAO-REF-00	Million hectares					
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
North America	234	235	236	237	241	244
Europe & Russia	339	337	336	334	334	334
Pacific OECD	57	57	57	57	60	61
Africa, sub-Saharan	226	245	265	284	301	315
Latin America	175	193	208	217	223	224
Middle East & N. Africa	67	69	70	72	73	74
Asia, East	147	146	146	146	145	145
Asia, South/Southeast	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	1002	1035	1063	1081
Rest of World	42	41	40	38	38	37
World	1561	1603	1643	1676	1707	1727

Source: IIASA world food system simulations; scenario FAO-REF-00, May 2009.

Cultivated land represents the physical amount of land used for crop production. In practice, part of the land is left idle or fallow, and part of the cultivated land is used to produce multiple crops within one year. The total harvested area in scenario FAO-REF-00 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.

Table 3.8: Harvested area (million hectares)

FAO-REF-00	Million hectares					
	2000	**2010**	**2020**	**2030**	**2040**	**2050**
North America	196	203	210	215	223	231
Europe & Russia	215	216	218	219	221	223
Pacific OECD	25	26	27	28	30	31
Africa, sub-Saharan	134	152	174	194	214	231
Latin America	126	143	160	171	179	180
Middle East & N. Africa	42	46	50	53	56	59
Asia, East	220	224	228	231	233	234
Asia, South/Southeast	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	1016	1055	1080
Rest of World	35	35	35	35	35	35
World	1306	1373	1441	1497	1547	1583

Source: IIASA world food system simulations; scenario FAO-REF-00, May 2009.

4. CLIMATE CHANGE IMPACTS ON CROP SUITABILITY AND PRODUCTION POTENTIAL

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

Scenarios of climate change were developed in order to estimate their effects on crop yields, extents of land with cultivation potential, and the number and type of crop combinations 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 gases) levels.

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

Table 4.1: Impacts of climate change on production potential of rain-fed wheat of current cultivated land (percent changes with respect to potential under current climate)

Region	Cultivated Land	Hadley A2, 2050s versus Reference Climate			
		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 Fed.	126	-1	-1	5	5
Central America & Carrib.	43	-48	-57	-45	-54
South America	129	-24	-26	-20	-22
Oceania & Polynesia	53	11	12	16	18
North Africa & 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
Middle 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 & 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	1563	-10	-11	-5	-5

Source: GAEZ 2009 simulations; May 2009.

The range of results computed in AEZ refers to different assumptions concerning autonomous adaptation in cropping and effects of CO2 fertilization on crop yields (e.g. see different columns in Table 4.1). The first variant is quantified without considering the effects of CO2 fertilization and assumes that farmer's would be able to change cropping dates and crop types but would be limited to local crop varieties, i.e. crop varieties with temperature characteristics and moisture requirements of LUT's used in current climate. The second column refers to results where CO2 fertilization is still not considered but best adapted plant types, e.g. available elsewhere and adapted to higher temperatures, would be available to maximize production potential. Variants 3 and 4 take into account effects of CO2 fertilization and quantify outcomes respectively with limited and full adaptation of crop types.

The results for wheat presented in Table 4.1 are based on a spatial climate change scenario derived from outputs of the UK HadCM3 model (Gordon et al., 2000; Pope et al.; 2000) for the IPCC SRES A2 emissions pathway (Nakicenovic et al., 2000).

Except for countries in Central Asia, the impact of climate change on wheat production in developing countries is generally negative. In contrast, rain-fed wheat production potential of current cultivated land in Europe, Russia and Oceania is increasing. The net global balance is projected to be a reduction of production potential by 2050s of five to ten percent.

Table 4.2: Impacts of climate change on production potential of rain-fed maize of current cultivated land (% changes with respect to potential under current climate)

Region	Cultivated Land	Hadley A2, 2050s versus Reference Climate			
		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 Fed.	126	61	61	66	67
Central America & Carrib.	43	1	5	5	9
South America	129	-3	2	0	6
Oceania & Polynesia	53	27	30	31	34
North Africa & 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
Middle 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 & 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	1563	2	5	6	9

Source: GAEZ 2009 simulations; May 2009.

Table 4.2 summarizes the simulated AEZ results for rain-fed grain maize. The global production potential of current cultivated land under projected HadCM3 climate conditions of the 2050s increases in all four variants owing to a modest increase (or only slight aggregated decrease) of the grain maize potential in developing countries and a significant improvement in developed regions. Despite this improvement at global level, there are also several regions where maize production potential decreases, including in Sub-Saharan Africa.

Table 4.3: Impacts of climate change on the production potential of rain-fed cereals in current cultivated land (percent changes with respect to potential under current climate)

Region	Cultivated Land	Hadley A2, 2050s versus Reference Climate			
		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 Fed.	126	3	3	9	9
Central America & Carrib.	43	-10	-6	-6	-2
South America	129	-8	-3	-4	1
Oceania & Polynesia	53	2	4	6	8
North Africa & 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
Middle 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 & 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	1563	-5	-2	0	3

Source: GAEZ 2009 simulations; May 2009.

Results compiled in Table 4.3 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 climate and for future climate conditions the most productive cereal type in each grid-cell of the spatial resource inventory. Results indicate a somewhat increasing global rain-fed production potential, provided CO_2 fertilization is effective and full adaptation of crop types is achieved; but climate change could as well result in a reduction of the global production of about 5 percent if these two aspects were not achieved. 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 rain-fed cereal production potential.

Table 4.4 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 ‘best’ outcomes of the four variants discussed above, i.e. assuming effective CO_2 fertilization and full agronomic crop adaptation.

Results suggest that for the next decades the global rain-fed 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 CO_2 fertilization effects materialize and farmers are prepared and empowered to fully adapt to a changing climate. It should also be noted that the results in Table 4.4 do not account for impacts of possibly increased climatic variability.

Table 4.4: Impacts of climate change on the production potential of rain-fed cereals in current cultivated land (% change with respect to current climate)

Region	Hadley A2 versus Reference Climate (% change; with CO_2 fertilization)								
	Rain-fed Wheat			Rain-fed Maize			Rain-fed Cereals		
	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 Fed.	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 & Polynesia	-8	18	9	12	34	58	-7	8	2
North Afr & 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
Middle 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 & 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.

Table 4.5 presents results for AEZ estimated rain-fed crop potentials of wheat, maize and sorghum (relative to reference climate) based on the CSIRO GCM climate projections for IPCC A2 emissions pathways. Estimates assume full adaptation of crop types and include effects of CO2 fertilization due to increased atmospheric CO2 concentrations. Table 4.6 summarizes changes relative to crop potentials of current climate but excluding CO2 fertilization effects on crop yield.

Table 4.5: Impacts of climate change on the production potential of major rain-fed cereals in current cultivated land (% change with respect to current climate)

Region	CSIRO A2 versus Reference Climate (% change; with CO_2 fertilization)								
	Rain-fed Wheat			Rain-fed Maize			Rain-fed Sorghum		
	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 Fed.	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 & Polynesia	4	11	4	19	31	57	4	9	7
North Afr & 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
Middle 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 & 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 4.6: Impacts of climate change on the production potential of major rain-fed cereals in current cultivated land (% change with respect to current climate)

Region	CSIRO A2 versus Reference Climate (% change; without CO_2 fertilization)								
	Rain-fed Wheat			Rain-fed Maize			Rain-fed Sorghum		
	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 Fed.	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 & Polynesia	2	6	-4	17	27	50	2	6	3
North Afr & 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
Middle 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 & 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 the HadCM3 and CSIRO climate projections for IPCC A2 emissions pathways, suggest three conclusions: (i) there are a number of regions where climate change poses a significant threat for food production; (ii) the global balance of food production potential for rain-fed cereal production of current cultivated land may slightly improve in the short-term; effective agronomic adaptation by farmers to a changing climate and the actual strength of the so-called CO2 fertilization effect on crop yields will be decisive factors to realize a positive global balance of food production potential; and (iii) beyond 2050, negative impacts of warming 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 must support strategies to cope with climate variability and extreme events, which may severely affect the welfare of the most vulnerable populations. In the long run, climate change, if not halted, will result in irreparable damages to arable land, water, and biodiversity resources, with eventually serious consequences for food production and food security.

5. IMPACTS OF CLIMATE CHANGE ON WORLD FOOD SYSTEM INDICATORS

The evaluation of the potential impacts of climate change on production and trade of agricultural commodities, in particular on cereals, was carried out in two steps. First, simulations were undertaken where current climate and atmospheric conditions would prevail. Second, yield impacts due to temperature and CO2 changes, as derived from the agro-ecological assessment, were simulated with the world food system model and compared to the respective outcomes without climate change. Assumptions and results for the reference projection were presented in section 3.

Data on crop yield changes were estimated with AEZ for different scenarios of climate change and were compiled to provide yield-impact parameterizations for the countries or regions covering the world in the world food system model. Yield variations caused by climate change were introduced into the yield response functions by means of a multiplicative factor impacting upon 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 to counteract altered performance of agriculture have been assumed beyond the farm-level adaptations resulting from economic adjustments of the individual actors in the national models The adjustment processes taking place in the different scenarios are the outcome of the imposed yield changes triggering changes in national production levels and costs, leading to changes of agricultural prices in the international and national markets; this in turn affects investment allocation and labor migration between sectors as well as reallocation of resources within agriculture.

Agricultural prices

Table 5.1 summarizes the outcomes of scenario simulations with regard to agricultural prices. It shows the price index deviation, in percent, relative to equilibrium prices calculated in the reference projection without climate change. Price indexes were calculated for (i) cereals, (ii) over all crops, and (iii) aggregate for crops and livestock production. Climate scenarios were constructed for both the HadCM3 (Gordon et al., 2000; Pope et al.; 2000) and CSIRO (Gordon and O'Farrell, 1997; Hirst et al., 1997) GCM model outputs of IPCC SRES A2 simulations. Results for simulations using the Hadley Centre climate model outputs are given with and without considering the effects of CO2 fertilization on crop yields. It should be noted again that the climate scenarios do not take into account the possibility of increased climate variability. Also, the results assume successful and full agronomic adaptation by farmers (as discussed in section 3).

Table 5.1: Impact of climate change on agricultural prices

Scenario	CO2 fertilization	Change of Price Index relative to Reference Climate (percent)			
		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 world food system simulations, May 2009.

Overall, there is only a small impact resulting on world market prices from climate change yield impacts in the decades until about mid-century. In fact, the CO2 fertilization effect and assumed autonomous adaptation to climate change more than compensate for negative yield impacts. Beyond 2050, negative yield impacts would dominate and cause price increases, for cereals in the 2080s simulated in the order of 20 percent. When CO2 fertilization effects are disregarded prices start to increase gradually already in the early decades and increases are projected to accelerate after 2050. In this case medium term effects on cereal prices would be in the order of 10 percent; in the long term, i.e. by 2080, simulated price increases approach 50 percent.

Cereal production and consumption

The impact of climate change on the production of cereals, resulting both from changes in land productivity as well as economic responses of actors in the system, is summarized in Table 5.2.

The model results present a fairly consistent response and geographical patterns in regional cereal production to climate change. At global level, taking into account economic adjustment of actors and markets, cereal production until 2050 falls within 1 percent of the results for the respective reference simulations without climate change when CO_2 fertilization and agronomic adaptation are considered. For the 2080s the percentage losses exceed 2 percent for both HadCM3 and CSIRO climate scenarios. When CO_2 fertilization effects are not considered then simulated global cereal production is 1.4 percent less than in the baseline in 2050 and more than 4.3 percent below in 2080 (some 165 million tons).

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

Table 5.2: Impacts of climate change scenarios on cereal production

	Change in cereal production compared to the Reference scenario (percent)											
	Hadley A2				CSIRO A2				Hadley A2, without CO2 fertilization			
	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 & Russia	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
Africa, sub-Saharan	-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
Mid. East & N. 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
Asia, East	0.1	0.7	2.0	-2.8	-2.2	-2.8	-3.4	-7.2	-0.6	-0.4	0.2	-5.3
Asia, South/Southeast	-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 world food system simulations, May 2009.

In the world of the 2050s and 2080s, consumers are assumed to be much richer than today and are largely separated from agricultural production processes. They earn their incomes mainly in the non-agricultural sector. Therefore, aggregate changes in consumption depend mainly on food prices and income levels rather than on local production conditions. Table 5.3 summarizes the changes in total cereal consumption (i.e. including food, feed, industrial and seed use, and waste) occurring in the world food system simulations in response to climate change.

Table 5.3: Impacts of climate change scenarios on cereal consumption

	Change in cereal consumption compared to the Reference scenario (percent)											
	Hadley A2				CSIRO A2				Hadley A2, without CO_2 fertilization			
	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 & Russia	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
Africa, sub-Saharan	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
Mid. East & N. 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
Asia, East	0.0	-0.1	0.1	-1.0	-0.4	-0.8	-1.4	-0.8	-0.2	-0.4	-0.7	-1.6
Asia, South/Southeast	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 world food system simulations, May 2009.

Table 5.3 shows a fairly uniform decline in cereal consumption in 2080s of about 2 percent globally (i.e. about 80 million tons reduction compared to 3.8 billion tons consumption in the reference simulation) and about 2.5 percent in developing countries for both climate model scenarios and with CO_2 fertilization effects accounted for. In the HadCM3 simulation without CO_2 fertilization effects the reduction is about 4 percent compared to a reference scenario without climate change.

Risk of hunger

Estimates of the number of *people at risk of hunger* vary greatly according to socioeconomic development trajectories, in particular assumed income levels and income distribution, and population numbers. Assumptions and results for the reference simulation were presented in section 3.According to this reference projection, the estimated number of undernourished would slowly decrease between 2010 to 2020 (to about 900 million), would fall to 760 million by 2030, to 530 million by 2050, and to some 150 million by 2080. For comparison, the changes in the estimated number of people at risk of hunger, at different time points and for three climate scenarios, are summarized in Table 5.4. It is worth noting that in these simulations the recorded climate change impacts on undernourishment are relatively small; in the early periods due to relatively small global yield impacts and small resulting price effects, in the long-term, when yield impacts become substantial, due to the improved socio-economic conditions and small absolute number of undernourished.

Table 5.4: Impact of climate change on risk of hunger

	Change in number of people at risk of hunger compared to Reference scenario (millions)								
	Hadley A2			CSIRO A2			Hadley A2, without CO_2 fertilization		
	2030	**2050**	**2080**	**2030**	**2050**	**2080**	**2030**	**2050**	**2080**
Africa, sub-Saharan	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 world food system simulations, May 2009.

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 socioeconomic development scenario underlying the projections of Agriculture Toward 2030/50, with solid economic growth and a transition to stable population levels after 2050, poverty, and with it hunger – though negatively affected by climate change – is a much less ubiquitous phenomenon than it is today.

Cultivated land

The results for changes in cultivated land use are summarized in Table 5.5 and results for impacts on the level of harvested area are shown in Table 5.6. As for other food system indicators discussed before, the changes in net cultivated area simulated in response to climate change scenarios up to 2050 are relatively small. Even when CO2 fertilization effects are not taken into account the additional land put under cultivation globally is less than 10 million hectares. Only after 2050, when climate change impacts become increasingly negative for crop yields, more additional land is put into production compared to the reference climate simulations. In 2080, the estimated increase is 10-13 million hectares of cultivated land in simulations with CO2 fertilization effects accounted for, and 26 million hectares in the case without CO2 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.

Table 5.5: Impact of climate change on net use of cultivated land

	Change in Cultivated Land compared to Reference scenario (million hectares)								
	Hadley A2			CSIRO A2			Hadley A2, without CO_2 fertilization		
	2030	**2050**	**2080**	**2030**	**2050**	**2080**	**2030**	**2050**	**2080**
Africa, sub-Saharan	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 world food system simulations, May 2009.

Table 5.6: Impact of climate change on harvested area

	Change in Harvested Area compared to Reference scenario (million hectares)								
	Hadley A2			CSIRO A2			Hadley A2, without CO_2 fertilization		
	2030	**2050**	**2080**	**2030**	**2050**	**2080**	**2030**	**2050**	**2080**
Africa, sub-Saharan	-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 world food system simulations, May 2009.

6. 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 biofuels production is spreading around the world in a growing number of countries.

A number of developed countries have embraced the apparent win-win opportunity to foster the development of biofuels in order to respond to the threats of climate change, to lessen their dependency on oil and to contribute to enhancing agriculture and rural development, which is, of course, also of concern to developing countries where more than 70 percent of the poor reside in rural areas. Countries such as the United States, Member States of the European Union, China, India, Indonesia, South Africa and Thailand have all adopted policy measures and set targets for the development of biofuels.

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

The conditioning factors of biofuels development at national level include the technical capabilities of biofuels as blending agents, the agro-ecological conditions and 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 savings of greenhouse gas emissions and climate change mitigation.

6.1 Overview of biofuels 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, detailing as one of its components the regional and global use of transport fuels. Second, pathways were chosen as to the role played by biofuels in the total use of transport fuels. Third, the assumptions were made explicit as to the role and dynamics of second-generation biofuel production technologies in each scenario, or conversely, what fraction of total biofuel production was expected to be supplied by first-generation feedstocks, i.e. being based on conventional agricultural crops (maize, sugar cane, cassava, oilseeds, palm oil, etc.). Data on current biofuel feedstock use, and assumptions and specification of biofuel scenarios used for the scenario analysis are described in detail in Fischer et al. (2009).

Future projections of transport fuel use

For describing regional energy futures we used the World Energy Outlook (WEO 2008) reference scenario published by the International Energy Agency (IEA, 2008a). In the WEO 2008 Reference Scenario, world primary energy demand grows by 1.6 percent per year on average in 2006-2030, from 11,730 Mtoe to just over 17,000 Mtoe (i.e. by about 45 percent). This projection embodies the effects of government policies and measures that were enacted or adopted up to mid-2008. The IEA World Energy Model (WEM) - a large-scale mathematical system designed to replicate how energy markets function – has been the principal tool used to generate the sector-by-sector and fuel-by-fuel projections by region or country (IEA, 2008a).

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

Table 6.1: Final consumption of transport fuels by region

WEO	Million tons oil equivalent (Mtoe)			
	2000	**2020**	**2030**	**2050**
North America	655	773	773	781
Europe & Russia	519	658	652	609
Pacific OECD	105	110	99	93
Rest of World	6	16	24	36
Africa	45	69	80	122
Asia, East	114	337	495	625
Asia, South	111	224	322	544
Latin America	149	253	285	332
Middle East & N. Africa	108	214	259	342
Developed	1236	1480	1460	1417
Developing	576	1174	1529	2068
World*	1962	2830	3171	3750

* World totals include international marine bunkers and international aviation

In terms of total final consumption of transport fuel the scenario projects an increase from 1962 Mtoe to 3171 Mtoe for the period 2000-2030. 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 simulations of the world food system, are summarized in Table 6.1.

Biofuels use and share in total final consumption of transport fuels

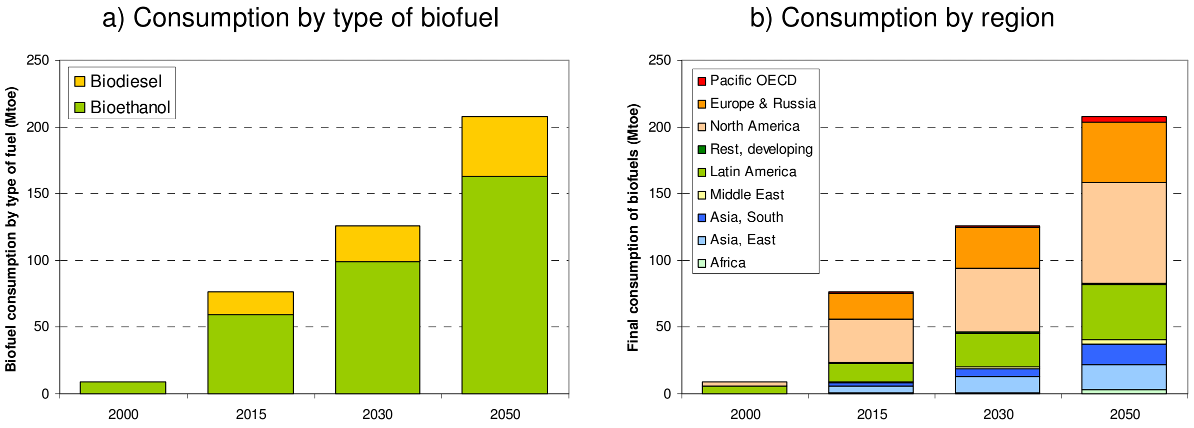
The level and regional pattern of total transport fuel consumption, as presented above, has been applied in all biofuels simulations with the world food system model discussed in this paper. Regarding the use of biofuels we implemented two alternative scenarios: (i) biofuel expansion based on the WEO 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.

Biofuels consumption in the WEO scenario

Final demand of biofuels in 1990 was about 6 Mtoe, with two-thirds being produced in Brazil at that time. In 2006 world biofuel consumption reached 24.4 Mtoe, with the United States being both the largest producer and consumer. In our implementation for 2020, final consumption of biofuels in the developed countries is projected at 63 Mtoe, with the United States and EU-27 accounting for 90 percent of this use. In 2030 the final consumption of biofuels reaches 79 Mtoe in the developed world. For 2030 and 2050 we use projections of biofuel consumption in developed countries that respectively amount to 79 Mtoe and 124 Mtoe[3].

Amongst the developing countries Brazil has been the pioneer producing about 5 Mtoe in 1990 and this is projected to increase to some 18 Mtoe in 2020. Total biofuel consumption in developing countries starts from about 5.5 Mtoe in 2000, increases to 31 Mtoe by 2020, and reaches 46 Mtoe 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 6.1 shows the dynamics of projected biofuel consumption in the WEO-based scenario; panel a) indicates the fuel split, panel b) shows a distribution by region.

Figure 6.1: Final consumption of biofuels in the WEO scenario



a) Consumption by type of biofuel

b) Consumption by region

Source: Fischer et al., 2009.

Biofuels consumption in the TAR scenario

The WEO 2008 report states that "… 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, 2008a, p.172)

A number of countries have defined mandatory, voluntary or indicative targets for transport fuels (see Table 6.2). 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 and termed target scenario (TAR). In this TAR scenario, final consumption of biofuels increases to 189 Mtoe in 2020, about twice the value achieved in WEO, and climbs to 295 Mtoe and 424 Mtoe respectively in 2030 and 2050. As hardly any country has announced biofuel targets beyond ca. 2020, this scenario should be interpreted as the extension of a rapid and ambitious biofuel development pathway based on targets announced up to 2020. It approximately doubles biofuel consumption compared to the WEO

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[3] Minor adjustments to values published in the WEO 2008 for developed countries have been implemented for use in the world food system simulations.

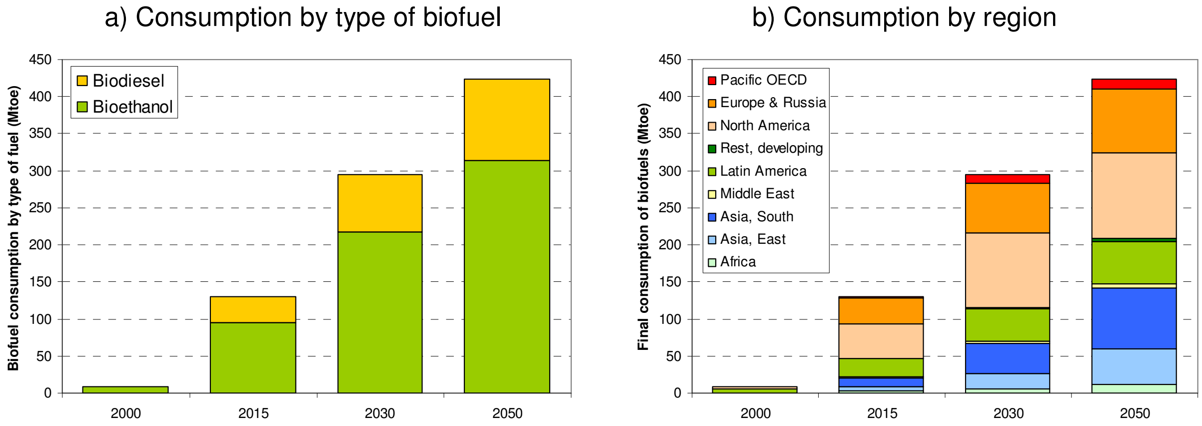
projections. Figure 6.2 shows distribution of biofuel consumption by type and region for the TAR scenario.

Table 6.2: Voluntary and mandatory targets for transport fuels in major countries

Country/Region	Mandatory, voluntary or indicative target
Australia	At least 350 million liters of biofuels by 2010
Canada	5% renewable content in gasoline by 2010
European Union	5.75% by 2010, 10% by 2020
Germany	6.25% by 2010, 10% by 2020
France	7% by 2010, 10% by 2015, 10 percent by 2020
Japan	0.6% of auto fuel by 2010; a goal to reduce fossil oil dependence of transport sector from 98% to 80% by 2030
New Zealand	3.4% target for both gasoline and diesel by 2012
United States	12 billion gallons by 2010, rising to 20.5 billion gallons by 2015 and to 36 billion gallons by 2022 (with 16 billion gallons from advanced cellulosic ethanol)
Brazil	Mandatory 25% ethanol blend with gasoline; 5 percent biodiesel blend by 2010.
China	2 million tons ethanol by 2010 increasing to 10 million tons by 2020; 0.2 million tons biodiesel by 2010 increasing to 2 million tons by 2020.
India	5% ethanol blending in gasoline in 2008, 10% as of 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, and 5% by 2020.
Thailand	2% biodiesel blend by 2008, 10% biodiesel blend by 2012; 10% ethanol blend by 2012.
South Africa	2% of biofuels by 2013

Source: Fischer et al., 2009.

Figure 6.2: Final consumption of biofuels in the TAR scenario


a) Consumption by type of biofuel

b) Consumption by region

Source: Fischer et al., 2009.

It is worth noting that in this TAR scenario the share of developing countries in total biofuel consumption is higher than in the WEO scenario due to considering fairly ambitious proposed or announced targets for China, India, Indonesia and Thailand. Due to this change in the regional distribution, the share of biodiesel in total biofuels increases somewhat compared to 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 a biofuels share in total transport fuel use in 2020 and 2030 at 2.7 percent and 3.0 percent respectively. At the global level this share comes to 3.5 percent in 2020 and 4.2 percent in 2030. It increases to 6 percent in 2050[4]. With a road transport share of 70 percent to 75 percent of total transport fuel use, biofuels would account for respectively 4.5 percent, 5.4 percent, and 7.6 percent of road transport in 2020, 2030 and 2050[5].

Share of second-generation biofuels in total biofuel consumption

In recent years second-generation biofuels, i.e. fuels produced from 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, but even more so because of their potential for production on 'non-food' land.

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 will be able to make a significant contribution.

Table 6.3: Scenario variants for share of second-generation biofuels in total

Scenario variant	Region	Assumed share of second-generation ethanol in total bioethanol (%)			
		2015	2020	2030	2050
WEO-V1, TAR-V1	United States	Starts	7.5	25	50
	Other OECD	None	Starts	12.5	33
	Russia	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
	EU-27	None	10	33	50
	Other OECD	None	10	33	50
	Russia	None	5	20	40
	China/India	Starts	5	20	40
	Other developing	0	0	10	20
TAR-V3	United States	10	35	55	70
	EU-27	10	31	47	67
	Other OECD	10	31	47	67
	Russia	Starts	10	33	50
	China/India	Starts	10	33	50
	Other developing	0	Starts	10	33

Source: Fischer et al., 2009.

For completing the definition of biofuel scenarios in this assessment, three variants were specified for both the WEO and TAR biofuel scenario. They represent alternative views/expectations on the dynamics of technology deployment for second-generation fuels. The variants are defined by describing different pathways for the share

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[4] Share in world total excludes international marine bunkers.

[5] Recent industry tests suggest that biofuels could also be successfully used in aviation.

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 6.3.

The variant V1 (both for WEO-V1 and TAR-V1) assumes that second-generation biofuel technologies will be available in the United States for commercial deployment as of 2015. By 2020, the lignocelluloses conversion will contribute 7.5 percent of total bioethanol, and by 2030 this share will increase to 25 percent. In other OECD countries it is assumed for this scenario variant that second-generation conversion plants will take off as of 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 would follow a somewhat slower path to contribute only 5 percent of 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 in this variant V2 on conventional feedstocks.

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

At the aggregate global level, second-generation biofuel shares in scenario variant WEO-V1 are 3 percent, 13 percent and 30 percent in 2020, 2030 and 2050 respectively. In scenario variant TAR-V1 these shares are respectively 2, 12 and 26 percent, i.e. somewhat lower due to the higher shares in total production achieved by developing countries[6] in the TAR scenario as compared to the WEO scenario. For variant TAR-V3, with an assumed accelerated second-generation development and deployment path, the respective shares are 22, 38, and 55 percent.

Sensitivity analysis with respect to share of biofuels in total transport fuels

In addition to the WEO and TAR biofuel scenarios introduced above, four sensitivity scenarios (SNS) were computed in order to systematically scan the world food system model outcomes for a broad range of imposed first-generation biofuel production levels, from 2-8 percent in 2020, 2.5-10 percent in 2030, and 3-12 percent in 2050. Table 6.4 summarizes for different scenarios and time points the assumed share of first-generation biofuels in total transport fuel use.

Table 6.4: First-generation biofuels assumed in sensitivity scenarios

Scenario	Share in total transport fuels (percent)			1st generation biofuel consumption (Mtoe)		
	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.

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[6] As developing countries on average are assumed to have a lower share of second-generation biofuels in total biofuel production than developed countries, their stronger participation in global biofuel production implies a lower global average share of second-generation fuels.

First-generation biofuel feedstocks demanded in selected biofuel scenarios

Estimates for 2008 indicate that about 80-85 million tons of cereals were used for ethanol production, mainly maize in the USA, and about 10 million tons of vegetable oil for production of biodiesel, dominated by the EU. In the reference scenario FAO-REF-01 these amounts are kept constant for the entire remaining 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 assumptions regarding availability of second-generation technologies. The amount of cereals and vegetable oil required for transport biofuel production in 2020, 2030 and 2050 in selected biofuel scenarios is shown in Table 6.5.

Table 6.5: Use of cereals and vegetable oil for biofuel production in different scenarios

Scenario	Cereals (million tons)			Vegetable oil (million tons)		
	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 world food system simulations, May 2009.

7. 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 an accelerated expansion of biofuel production, evaluated in the context of the world food economy and global resource base.

The previous sections briefly presented the analysis framework used in this study and the key assumptions regarding economic development and transport energy demand, in particular use of first- and second-generation biofuels. Internally consistent sets of assumptions were formulated as model scenarios and used to quantify impacts of expanding biofuel use on agriculture and world food system outcomes. In total ten such scenarios were analyzed; the acronyms used and a brief description is given in Table 7.1.

Table 7.1: Biofuel scenarios analyzed in this study

Scenario acronym	**Scenario description**
FAO-REF-00	Starting in 1990, assumes a world without any agricultural crops used for biofuel production.
FAO-REF-01	Assumes historical biofuel development until 2008; biofuels feedstock demand is kept constant after 2008; used as a reference simulation to which alternative biofuel scenarios are compared for their impact.
WEO-V1	Assumes transport energy demand and regional biofuel use as projected by International Energy Agency (IEA) in its WEO 2008 Reference Scenario. Second-generation conversion technologies become commercially available after 2015; deployment is gradual (see Table 6.3)
WEO-V2	Assumes transport energy demand and regional biofuel use as projected by IEA in its WEO 2008 Reference Scenario. Assumes that due to delayed arrival of second-generation conversion technologies all biofuel production until 2030 is based on first-generation feedstocks.
TAR-V1	Assumes transport energy demand as projected by IEA in its 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 compared to WEO 2008. Second-generation conversion technologies become commercially available after 2015; deployment is gradual (percentage as in WEO-V1)
TAR-V3	Assumes transport energy demand as projected by IEA in its 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	Sensitivity scenarios assuming low (V1), intermediate (V2), high (V3), and very high (V4) share of first-generation biofuels in total transport fuels (see Table 6.4).

The evaluation of the impacts of additional demand for first-generation biofuels on production, consumption, and trade of agricultural commodities, in particular on food staples, was carried out by comparing the results of a range of biofuel-expansion scenarios to a reference projection of the world food system simulated without imposing additional biofuel demand. Results of the reference projection were presented in section 3.

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

- Share of transport energy to be supplied from biofuels;
- Sensitivity of results to development speed of second-generation technologies.

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

Agricultural prices

As is to be expected in a general equilibrium world food system 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 7.2: Impacts of biofuel expansion scenarios on agricultural prices

Scenario	Change of Price Index relative to Reference scenario FAO-REF-01 (percent)								
	Cereals			Crops			Agriculture		
	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

Source: IIASA world food system simulations; scenario FAO-REF-01, May 2009.

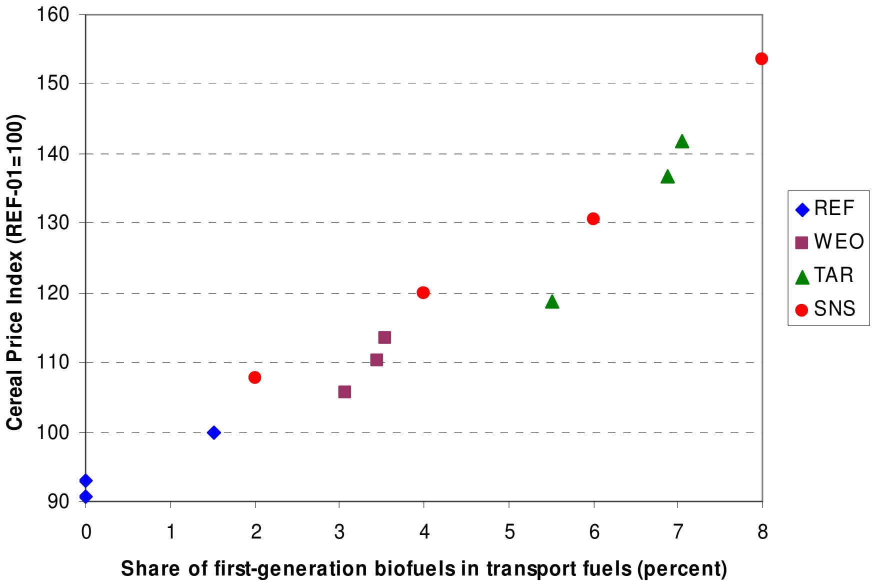
Table 7.2 shows the results for selected scenarios, namely biofuel demand according to WEO projections in scenario variants WEO-V1 and WEO-V2 (the latter assuming delayed introduction of second-generation technologies) and high biofuel consumption levels according to the TAR scenario in variants TAR-V1 and TAR-V3 (accelerated introduction of second-generation biofuels).

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 further crop price increases. For biofuel demand specified in the TAR scenario (i.e. about twice the level projected in the WEO scenario) the impact on crop prices in 2020 is fairly substantial, of the order of 35 percent. With accelerated introduction of cellulosic ethanol, as assumed in TAR-V3, the price impact on cereals would be halved to about 19 percent.

For 2030 the pattern of price impacts remains similar to 2020. As second-generation biofuels gain importance towards 2030, the differences in price impacts between WEO-V1 and WEO-V2 variants 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.

Summarizing over all scenario experiments, we find that agricultural prices considerably depend on the aggregate share that first-generation biofuels are mandated to contribute to total transport fuel consumption. This is shown in Figure 7.1.

Figure 7.1: Cereal price index versus share of first-generation biofuels in transport fuels, in 2020



Source: IIASA world food system simulations, May 2009.

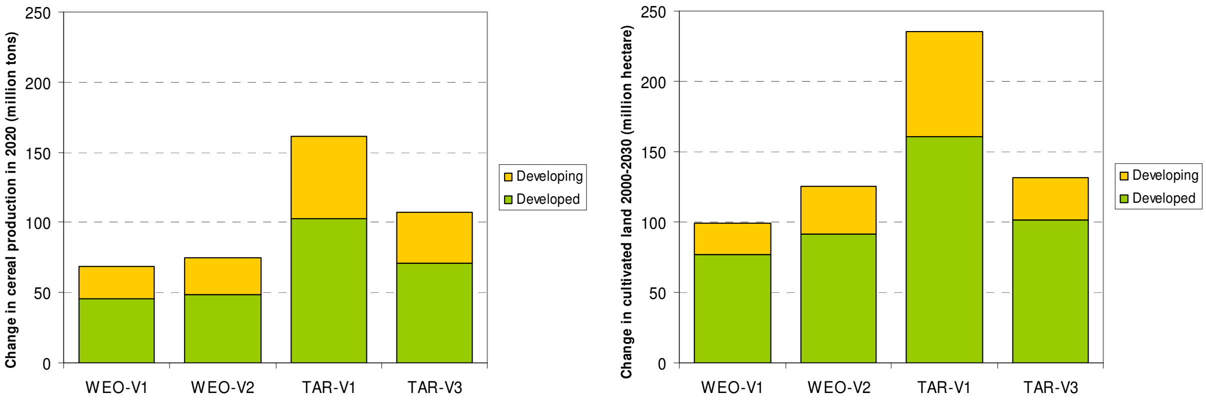
Note: SNS = sensitivity scenarios; TAR = scenario simulations based on mandates and indicative voluntary targets; WEO = simulations based on WEO 2008 projections of biofuel demand; REF = reference projections with constant, decreasing or no biofuel demand beyond 2008).

Cereal demand and production

The rising agricultural prices in the biofuel scenarios provide incentives on the supply side, for intensifying production and for augmenting and reallocating land, capital and labor. At the same time, consumers react to price increases and adjust their patterns of consumption. Figure 7.2 shows the producer response of cereal sectors for different biofuel scenarios in 2020 and 2030, i.e. the amount of additional cereal production realized in each scenario compared to REF-01.

Figure 7.2: Change in cereal production relative to baseline FAO-REF-01, in 2020

a) in 2020 b) in 2030



Source: IIASA world food system simulations, May 2009.

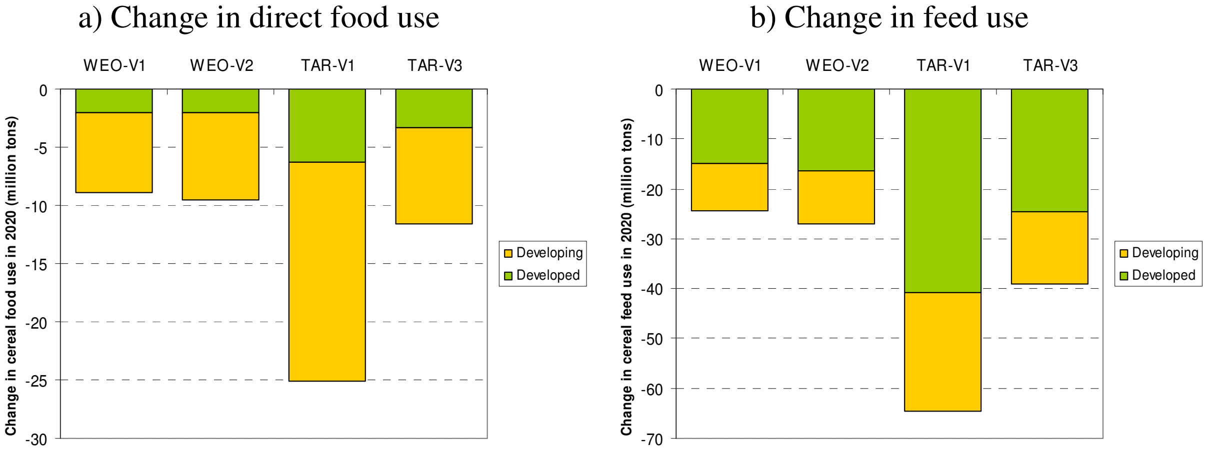
Table 7.3: Impacts of biofuel expansion scenarios on cereal production and demand

Scenario	Change of Cereal Production and Demand relative to Reference scenario FAO-REF-00 (million tons)								
	2020			2030			2050		
	Biofuel use	Production	Food/ feed	Biofuel use	Production	Food/ feed	Biofuel use	Production	Food/ feed
REF-01	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

Source: IIASA world food system simulations; compared to reference scenario FAO-REF-00, May 2009.

In 2020, the additional (compared to 83 million tons representing 2008 levels) global use of cereal commodities for ethanol production relative to the reference simulation FAO-REF-01 is around 100 million tons in WEO-V1 and WEO-V2, 240 million tons in TAR-V1 and 155 million tons in scenario TAR-V3. Figure 7.2 highlights that production increases in response to higher agricultural prices are stronger in developed countries, as are the reductions in feed use (see Figure 7.3). When it comes to 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 negatively affect lower income consumers more than higher income consumers. First, lower-income consumers spend a larger share of their income on food and second, staple food commodities such as corn, wheat, rice, and soybeans account for a larger share of their food expenditures. Responses on the consumer side, reduced food and feed use of cereals, are shown in Figure 7.3.

Figure 7.3: Change of cereal use relative to baseline FAO-REF-01, in 2020


a) Change in direct food use

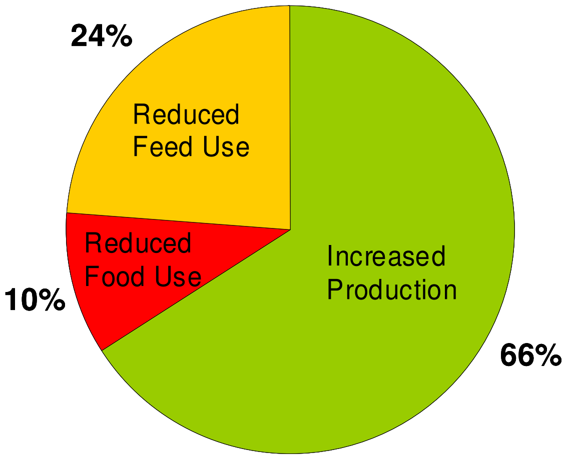
b) Change in feed use

Source: IIASA world food system simulations; May 2009.

Box 7.1: 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 ten percent of the amount of cereals used for biofuel production, reduced feed use accounts for about a quarter.

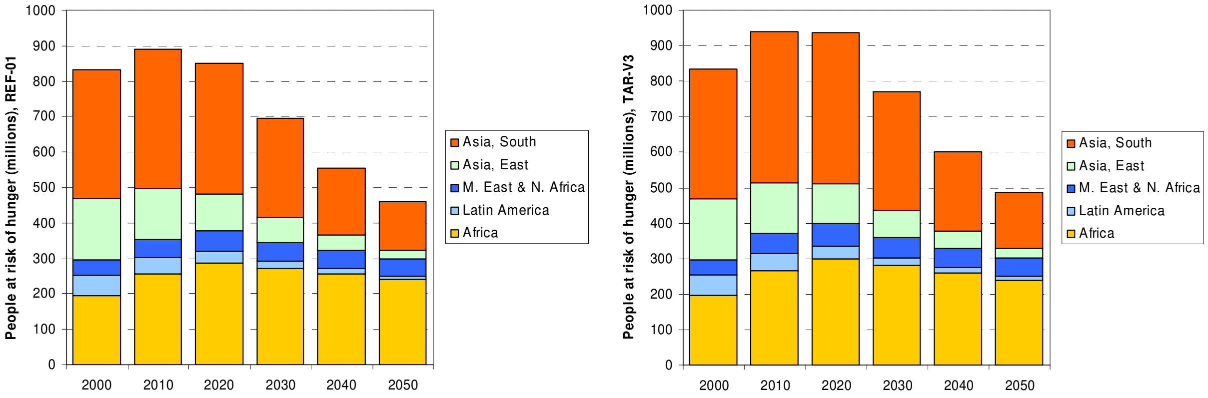


Source: IIASA world food system simulations; May 2009.

Risk of hunger

The estimated number of people at risk of hunger used in the world food system 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 relative to average national per capita food requirements.

Figure 7.4: Risk of hunger in FAO-REF-01 and TAR-V3 scenarios, developing countries



a) Scenario FAO-REF-01 b) Scenario TAR-V3

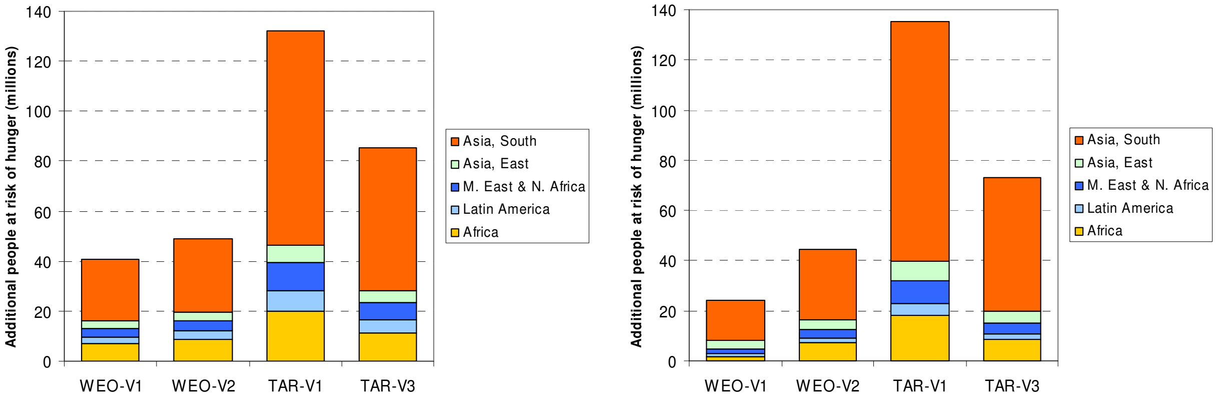
Source: IIASA world food system simulations; May 2009.

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. Consequently this reduces food consumption in developing countries, which in turn in the simulations results in an increased number of people at risk of hunger. Figure 7.4 shows a comparison of results until 2050 for the baseline scenario FAO-REF-01 (no climate change and no additional biofuel demand after 2008) versus estimated number of people at risk of hunger in the TAR-V3 scenario, i.e. when implementing an ambitious global biofuel target with swift introduction of second-generation technologies.

While in the reference scenario FAO-REF-01 the number of undernourished people peaks in 2009/10 at somewhat more than 890 million and then declines (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 at about 940 million and only then starts to decline as second-generation production begins to take pressure off the competing food-feed-biofuel feedstock markets.

Figure 7.5 presents the simulated regional distribution of additional undernourished in different biofuel scenarios, showing a large impact in particular in South Asia. It is worth noting that even with relatively swift deployment of second-generation technologies, as assumed in scenario TAR-V3, the results for 2020 show an increase of 80 million undernourished people.

Figure 7.5: Additional people at risk of hunger relative to baseline FAO-REF-01



a) in 2020

b) in 2030

Source: IIASA world food system simulations; May 2009.

The reference scenario REF-01, keeping biofuels consumption constant after 2008, projects for developing countries the number of undernourished people in 2020 and 2030 at respectively 850 and 700 millions. The biofuels target scenario estimates for developing countries that an additional 132 and 136 million people will be at risk of hunger in 2020 and in 2030 respectively. In the biofuels target scenario, with accelerated second-generation biofuels deployment, the corresponding number of additional people at risk of hunger decreased to 85 million and 74 million respectively in 2020 and 2030. Africa and South Asia account for more than two-thirds of the additional population at risk of hunger in developing countries across biofuels scenarios in 2020 as well as in 2030.

Value added of crop and livestock production

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 has considered as to what extent the additional production of crops developed on arable land as feedstocks for biofuels production will increase value added in agriculture. The percentage changes relative to the reference scenario FAO-REF-00, without any biofuels, is shown in Table 7.4.

Table 7.4 highlights that for all biofuels scenarios agricultural value added increases at the global and regional levels, as indeed expected. For instance for scenario WEO-V1 (with relatively modest biofuels development), the changes in absolute terms amount to US1990$ 41 billion in 2020, 57 billion in 2030 and 71 billion in 2050. The developed countries account initially 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, amounting to about 50 percent in 2030, and on average 45 percent of the projected gains in 2050. Table 7.4 also shows that agricultural sectors in developed countries benefit relatively more than in developing countries in terms of percentage gains relative to the baseline. In scenario WEO-V1 the increase in 2020 relative to scenario REF-00 recorded for developed countries is 4.3 percent compared to 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 for the Middle East & North Africa region and for Asian regions is only 0.9 to 1.9 percent.

Table 7.4: Impacts of biofuel expansion scenarios on agricultural value added

Scenario	Change of Agricultural Value Added relative to Reference scenario FAO-REF-00 (percent)								
	World			Developed countries			Developing countries		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
REF-00	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 world food system simulations; reference scenario FAO-REF-00, May 2009.

Table 7.5: Impacts of biofuel expansion scenarios on regional agricultural value added

Region	Change of Agricultural Value Added relative to Reference scenario FAO-REF-00 (percent)								
	Scenario WEO-V1			Scenario WEO-V2			Scenario TAR-V3		
	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 & Russia	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
Africa, sub-Saharan	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
Middle East & N. Africa	1.9	2.1	2.7	2.0	2.2	2.9	3.4	3.9	3.6
Asia, East	0.9	1.1	1.2	0.9	1.2	1.4	1.3	1.5	1.7
Asia, South/Southeast	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
Rest of World	1.2	1.2	1.1	1.3	1.4	0.5	2.6	3.0	2.4
World	2.5	3.1	3.2	2.5	3.5	4.0	3.7	4.9	4.5

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

In scenario TAR-V1, with a high demand for first-generation biofuels due to high national targets and only gradual introduction of second-generation technologies, crop and agriculture value added increases substantially, globally by some 6.6 percent by 2030. Global agricultural value added is higher by 73 billion US1990$ in 2020, 120 billion in 2030, and 155 billion in 2050. Again, the percentage gains in scenario TAR-V1 are higher for developed countries (about 6.9 percent in 2020) compared to developing regions (average 3.4 percent increase in 2020) where estimated gains fall in a range of 1.7 to 5.7 percent. The biofuels target scenario TAR-V1 estimates the increase in agriculture value added (measured in constant 1990 US$) as a result of biofuels development at US$ 33 billion and US$ 62 billion in the developed countries in 2020 and 2030 respectively. The corresponding values for the developing countries are US$ 37 billion and US$ 51 billion respectively.

Impacts on the use of cultivated land

The 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: first, direct land use changes, i.e. estimating the extent of land that is used for producing biofuel feedstocks; secondly, the estimation of indirect land use effects, which can result from bioenergy production displacing services or commodities (food, fodder, fiber products) on arable land currently in production.

The approach pursued in this study is to apply a general equilibrium framework that can capture both direct and indirect land use changes by modeling responses of consumers and producers to price changes induced by introducing competition with biofuel feedstock production. This approach accounts for land use changes but also considers production intensification on existing agricultural land as well as 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 scenario FAO-REF-00, the expansion of arable land to meet growing food and feed requirements during 2000 to 2020 amounts to about 80 million hectares of additional land put into cultivation. Africa and Latin America, with a projected increase of cultivated land of respectively 39 million and 33 million hectares, account for more than 85 percent of total net arable land expansion.

Table 7.6: Impacts of biofuel expansion scenarios on cultivated land use

Scenario	Change of Cultivated Land relative to Reference scenario FAO-REF-00 (percent)								
	World			Developed countries			Developing countries		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
REF-00	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

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

Table 7.6, shows the *additional* use of cultivated land in 2020, 2030 and 2050 in comparison to a scenario without any crop-based biofuels. For the WEO and TAR biofuel scenarios shown this additional use of cultivated land in 2020 falls in the range of 19 million hectare (scenario WEO-V1) to 38 million hectares (scenario TAR-V1). For developed countries the arable land use increases in different biofuel scenarios during 2000-2020 in the range of 6 to 12 million hectares, compared to a net decrease by 3 million hectares in a scenario without biofuels. Developing countries record in the baseline without biofuels (scenario FAO-REF-00) an increase of arable land use during 2000-2020 that amounts to 87 million hectares; for comparison, additional crop demand due to biofuel development results in a total expansion of cultivated land use of 99 to 112 million hectares, and additional use of 12 to 24 million hectares. The difference of 24 million hectares arable land use in developing countries in scenario TAR-V1 (compared to the results without biofuel demand) is mainly explained by an additional expansion of 9 million hectares in sub-Saharan Africa and 11 million hectares in South America.

When looking at differences in expansion of cultivated land for the period 2000 to 2030, then the range of estimates for biofuel scenarios relative to the baseline (without biofuels) widens further, from an additional use of 19 million hectares (scenario WEO-V1) to 46 million hectares (scenario TAR-V1).

For the full range of simulated scenarios (including sensitivity scenarios) the use of cultivated land in 2020 goes from 1643 million hectares to 1691 million hectares, a difference of 48 million hectares. In 2030 it ranges from 1676 million hectares to 1734 million hectares, i.e. a maximum additional use of 58 million hectares.

Table 7.7: Impacts of biofuel expansion scenarios on harvested area

Scenario	Change of Harvested Area relative to Reference scenario FAO-REF-00 (percent)								
	World			Developed countries			Developing countries		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
REF-00	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

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

Increases of harvested area account for both the expansion of cultivated land as well as increased multi-cropping, i.e. the intensification of cropping in existing cultivated land. For the WEO and TAR biofuel scenarios this *additional* harvested area falls in the range of 26 million hectares (scenario WEO-V1) to 59 million hectares (scenario TAR-V1). In developed countries the harvested area increases in different biofuel scenarios by 10 to 18 million hectares, in developing by 17 to 35 million hectares. While Africa and South America accounted for more than 80 percent of physical land expansion (i.e. 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.

In summary, while total global arable land use increases by only 1-3 percent in different biofuel scenarios compared to a situation without biofuels - a number that may seem small at first sight – the impact becomes substantial when expressed in terms of net cultivated land expansion during respectively 2000-2020, 2000-2030, and 2000-2050. From this perspective, the impact of biofuel scenarios is to increase the net expansion of cultivated land during 2000-2020 by 20-45 percent, by 15-40 percent over the period 2000-2030, and by 12-30 percent during 2000-2050.

8. SECOND-GENERATION BIOFUELS

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

In this situation, second-generation biofuels, produced from woody or herbaceous non-food plant materials as feedstocks, have attracted great attention in the hope that substantial technological and economic barriers, which still hamper a commercial deployment of second-generation technologies, can be resolved in the near future and that they will soon become fully commercialized.

Some of the problems associated with first-generation biofuels can be avoided by the production of biofuels manufactured from agricultural and forest residues and from 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 secondly different quality land could possibly be used for production, thus limiting or avoiding land use competition with food production as lignocellulosic feedstocks are expected to be mainly grown outside cultivated land.

Following substantial government grants recently made to develop second-generation feedstocks and conversion technologies, and based on the announced plans of companies developing second-generation biofuel facilities, an optimistic view is that first 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 by 2030 to meeting the global transport fuel demand (IEA, 2008b).

Uncertainties have been included in the scenario analysis by simulating the outcomes for a range of assumptions on the expected share of biofuels that will be contributed by second-generation fuels (see Table 8.1).

Table 8.1: Share and total amount of second-generation biofuels, by scenario

Scenario	Share of second-generation fuels in total transport biofuels (percent)			Use of second-generation biofuels (Mtoe)		
	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.

A recent report published by the IEA states that both principal conversion processes, the biogeochemical conversion of cellulose to ethanol and the thermo-chemical conversion to FT-diesel, can potentially convert 1 dry ton of biomass (with about 20 GJ/ton energy content) to around 6.5 GJ of energy carrier in the form of biofuels, i.e. an overall biomass to biofuel conversion efficiency of about 35 percent (IEA, 2008b). Ranges of indicative biofuel yields per dry ton of biomass are shown in Table 8.2.

Table 8.2: Indicative biofuel yields of second-generation conversion technologies

	Biofuel yield (liters/dry ton)		Energy content (MJ/liter)	Energy yield (GJ/dry ton)		Biomass input (dry ton/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 (2008b)

Assuming that on average biochemical ethanol yields of 250 liters per dry ton biomass will be achievable in 2020 and 300 liters per dry ton in 2030, and respectively 160 liters per dry ton and 200 liters per dry tons will result from thermo-chemical Fischer-Tropsch diesel conversion, then for each ton oil equivalent of second-generation biofuels an average 7.7 dry tons biomass are needed in 2020 and 6.4 dry tons by 2030. A value of 6 dry tons per toe is assumed for 2050. This results in a biomass demand for second-generation biofuels as listed in Table 8.3.

Table 8.3: Biomass demand for second-generation biofuels, by scenario

Scenario	Global biomass demand for second-generation biofuels (million dry tons)			Biomass demand for second-generation biofuels in developed countries (million dry tons)		
	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	1402	297	583	875

Source: Fischer et al., 2009.

Rapid deployment of second-generation conversion technologies after 2015 in order to meet the biofuel production of the target (TAR-V3) scenario in 2020 and 2030 would require some 315 million dry tons of biomass in 2020, increasing to 725 million dry tons in 2030. Of this about 300 million dry tons in 2020 and nearly 600 million dry tons would be required to meet 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 logistical systems but no additional land is needed. 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 establishing plantations of perennial energy grasses or short rotation forest crops. Typical yields for the most important suitable feedstocks are summarized in Table 8.4.

Table 8.4: Typical yields of second-generation biofuel feedstocks[7]

	Current yields (dry tons/hectare)	Expected yield by 2030 (dry tons/hectare)
Miscanthus	10	20
Switchgrass	12	16
Short rotation willow	10	15
Short rotation poplar	9	13

Source: Worldwatch Institute (2007)

Taking an average typical yield of around 10 dry tons per hectare as possible and reasonable in 2020, then the biomass requirements listed in Table 8.3, a maximum of 315 million dry tons in 2020, implies that up to 32 million hectares of land would be needed if all biomass were to come from plantations. In reality the land requirement in 2020 will be much lower due to large amounts of cheap crop and forest residues available. In this early stage of second-generation biofuel development most of the biomass would be required in developed countries. By 2030, assuming that research as well as learning would increase average yields to about 15 dry tons per hectare (as suggested in Table 8.4), then an upper limit of land required for feedstock production would be 50 million hectares in the TAR-V3 scenario and less than 20 million hectares in both WEO-V3 and TAR-V1 scenarios.

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

While conventional agricultural feedstocks currently used in first-generation biofuel production compete with food crops, second-generation lignocelluloses technologies promise substantial greenhouse gas savings and may permit tapping into land resources currently not or only extensively used. Acknowledging these significant advantages of second-generation lignocellulosic biofuel feedstocks over conventional agricultural feedstocks, we employed a detailed geographical resource database (Fischer et al., 2008) to estimate 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 excluding forests.

In this estimation, based on a 5′ by 5′ latitude/longitude grid (i.e. about 10 km by 10 km at the equator), we started from total land area and subtracted all land indicated as artificial and built up surfaces, all cultivated land and current forest land. In a next step all areas indicated or designated as legally protected were excluded. Then land was excluded with very low productivity, either due to cold temperatures in the high latitudes or high altitudes, or because of low annual precipitation, as well as land unsuitable because of steep sloping conditions.

Excluding from a total global land area of 13.2 billion hectares (excl. Antarctica and Greenland) all current cultivated land, forests, built-up land, water and non-vegetated land (desert, rocks, etc.) resulted in 4.6 billion hectares remaining land area (ca. 35 percent of total). Excluding from these extents the unproductive, very low productive (e.g. tundra, arid land) or steeply sloped land, a remaining area of 1.75 billion hectares (see Table 8.5) was estimated, which comprises of grassland and woodland.

Table 8.5: Regional balance of land classified as unprotected grassland and woodland potentially useable for rain-fed lignocellulosic biofuel feedstock production

Region	Total grassland and woodland (mill. ha)	Of which			Potential rain-fed yield		
		Protected areas (mill. ha)	Unproductive or very low productive (mill. ha)	Balance of grassland and woodland (mill. ha)	Average yield (dry t/ha)	Low yield (dry t/ha)	High yield (dry t/ha)
North America	659	103	391	165	9.3	6.7	21.4
Europe & Russia	902	76	618	208	7.7	6.9	14.5
Pacific OECD	515	7	332	175	9.8	6.5	20.0
Africa	1086	146	386	554	13.9	6.7	21.1
Asia, East	379	66	254	60	8.9	6.4	19.0
Asia, South	177	26	81	71	16.7	7.6	21.5
Latin America	765	54	211	500	15.6	7.1	21.8
Middle East & N. Africa	107	2	93	12	6.9	6.3	10.6
Developed	2076	186	1342	548	8.9	6.7	21.0
Developing	2530	295	1029	1206	14.5	6.8	21.5
World	4605	481	2371	1754	12.5	6.8	21.5

Source: Fischer et al., 2008.

Over two-thirds of this grassland and woodland potentially suitable for biofuels feedstock production is located in developing countries, foremost in Africa and South America (see Table 8.5). These estimates are to be understood as indicative only and are subject to the limitations and accuracy of global land cover, soil and terrain data.

An important current use of these land resources is livestock grazing. Using available UN FAOSTAT data on feed utilization of crops and processed crop products (e.g. oilseed cakes and meals), production of fodder crops, national livestock numbers and livestock production, we estimated the feed energy provided by these recorded sources in each country in order to determine the energy gap to be filled by grassland and pastures. The results of detailed livestock feed energy balances suggest that in year 2000 about 55-60 percent of the available grassland biomass globally was required for animal feeding. This share is about 40 percent in developed countries. It amounts to an average 65 percent for developing countries, with values for Asian regions larger than 80 percent and 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 in the order of 700 – 800 million hectares, characterized by a rather wide range of productivity levels. Of these extents an estimated 330 million hectares are in the developed countries (about one-third each in North America, Europe & Russia & Central Asian republics, and Pacific OECD). About 450 million hectares of this land were estimated for the developing countries; 275 million hectares in Africa and 160 million hectares in Latin America. Some regional details of the estimated land areas and potential yields of second-generation lignocellulosic feedstocks are presented in Table 8.5.

We have subtracted only the demand for livestock feeding as the main current alternative use. No allowances were included for other social or environmental functions of the land, e.g. as feed source for wildlife. Also, estimates are subject to uncertainties regarding grass and pasture yields, which due to scarcity of measured data had to be estimated in model simulations with the IIASA/FAO 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 hectares) and in 2030 (about 50 million hectares) could be met without having to compete for cultivated land. The results of the biofuels target scenario with accelerated second-generation biofuels deployment indicate that production of lignocellulosic feedstocks on some 100 million hectares would be sufficient to achieve the biofuels target share in world transport fuels in 2050.

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

9. COMBINED IMPACTS OF CLIMATE CHANGE AND EXPANSION OF BIOFUEL PRODUCTION ON WORLD FOOD SYSTEM INDICATORS

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

Agricultural prices

Table 9.1 presents the results of scenario analysis and lists deviations of price indexes for cereals, all crops, and for 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.

Comparing these results with outcomes listed in earlier Table 5.1 (climate change impacts) and Table 7.2 (biofuel expansion impacts) indicates that the effects of both factors will combine to increase agricultural prices. For very next decades to come the more important scenario factor in determining price increases is the scale of crops used as biofuel feedstocks. In the medium- and long-term, climate change becomes the overriding factor.

Taking effects of CO_2 fertilization on crop yields into account, the simulated cereal price increases for the presented scenario combinations up to 2050 fall in the range of 15-40 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 fall in the range of 20-55 percent. Simulated results for the 2080s, when climate change impacts seriously affect crop yields, the calculated cereal price increases are respectively in the range of 40-60 percent (with CO_2 fertilization) and 70-90 percent (without CO_2 fertilization).

Table 9.1: Combined impact of climate change and biofuel expansion scenarios on agricultural prices

Scenario	CO_2 fertilization	Change of Price Index relative to Reference Climate (percent)			
		2020	2030	2050	2080
Cereals					
Hadley A2, 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

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

Cereal production and consumption

Table 9.2 lists the scenario results with respect to production increases relative to the baseline scenario REF-00 (without climate change and no crop use for biofuel production).

Table 9.2: Combined impact of climate change and biofuel expansion scenarios on production of cereals

Scenario	CO_2 fertilization	Change of cereal production relative to production in reference scenario FAO-REF-00 (million tons)			
		2020	2030	2050	2080
Production					
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

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

Table 9.3: Combined impact of climate change and biofuel expansion scenarios on consumption (excl. biofuel use) of cereals

Scenario	CO_2 fertilization	Change of cereal consumption (excluding biofuel feedstocks) relative to reference scenario FAO-REF-00 (million tons)			
		2020	2030	2050	2080
Consumption					
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

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

Comparing these scenario results with the information in Table 7.3 (impact of biofuel expansion scenarios) indicates that there is up to 2050 relatively little impact of climate change on aggregate cereal supply and consumption for the HadCM3 scenario with CO2 fertilization; with CSIRO GCM derived climate change impacts the shortfall in consumption increases by about 20 million tons compared to biofuels only. Without CO2 fertilization effect on crop yields, the decrease in consumption for HadCM3 in 2030 is 68-148 million tons of which about 25 million tons is due to climate change. In 2050 the consumption reduction is in the range of 104-174 million tons of which about 50 million tons is caused by climate change. In the long-term, i.e. results for the 2080s, climate change accounts for up to two-thirds of the reduction in cereal consumption in scenarios with CO2 fertilization and for up to 85 percent in the HadCM3 scenario without CO2 fertilization.

Risk of hunger

Combined scenario results regarding the indicator of number of people at risk of hunger are shown in Table 9.4. Results are consistent with the previous discussion on price changes and cereal consumption impacts. Note again that the conditions portrayed by the FAO Agriculture Toward 2030/50 reference projections imply a vast improvement in reducing undernourishment. Therefore relative changes compared to baseline REF-00 are large in 2050s and 2080s but relative small in absolute terms.

Table 9.4: Combined impact of climate change and biofuel expansion scenarios on risk of hunger indicator

Scenario	CO_2 fertilization	Change of estimated number of people at risk of hunger relative to reference scenario FAO-REF-00 (millions)			
		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

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

Cultivated land

Finally, Table 9.5 and Table 9.6 present the combined impact of climate change and biofuel expansion scenarios on cultivated land use. Summarizing over all scenarios shown in Table 9.5, the additional use of cultivated land in 2020 falls in the range of 16-40 million hectares, 17-49 million hectares in 2030, and 20-58 million hectares in 2050.

Table 9.5: Combined impact of climate change and biofuel expansion scenarios on use of cultivated land

Scenario	CO_2 fertilization	Change of cultivated land relative to reference scenario FAO-REF-00 (million hectares)			
		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

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

For harvested area, as shown in Table 9.6, the additional use in 2020 falls in the range of 24-59 million hectares, 28-78 million hectares in 2030, and 28-85 million hectares in 2050.

Table 9.6: Combined impact of climate change and biofuel expansion scenarios on harvested area

Scenario	CO_2 fertilization	Change of harvested area relative to reference scenario FAO-REF-00 (million hectares)			
		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

Source: IIASA world food system simulations; reference scenario FAO-REF-00, May 2009.

10. CONCLUSIONS

This paper reports on a large number of scenario experiments conducted to better understand 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. Main conclusions and implications derived from the global quantitative analysis are summarized below.

- 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 socioeconomic and, even more so, the technological characteristics of different development futures strongly affect the capability of societies to adapt to and mitigate climate change.
- Assumptions regarding yield increases due to increased atmospheric CO_2 concentrations (the so-called CO_2 fertilization effect) play an important role in scenario outcomes. When disregarding the CO_2 fertilization effect, negative climate change impacts on crop yields and world food system indicators are noticeable already in the short term and are very substantial in the medium and long-term.
- 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 when expansion follows the pace projected by the IEA in 2008, or achieves levels implied by the 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 reduce over time. The opposite is to be expected for climate change impacts.
- For the range of scenarios analyzed in this assessment, the combined impact of climate change and biofuel expansion on aggregate crop prices is in the range of a 10-45 percent increase. Decrease of cereal consumption typically falls within 35-100 million tons initially, increasing to a range of 60-150 million tons by 2050. In terms of cultivated land, an additional use in the range of 20-50 million hectares by 2030 and of 25-60 million hectares in 2050 can be expected.

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ANNEX 1: THE MODELING FRAMEWORK

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

AEZ methodology

The AEZ modeling 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., 2002a; 2005). This land-resources inventory is used to assess, for specified management conditions and levels of inputs, the suitability of crops in relation to both rain-fed and irrigated conditions, and to quantify expected attainable production of cropping activities relevant to specific agro-ecological contexts. The characterization of land resources includes components of climate, soils, landform, and present land cover. Crop modeling 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 (LUT) database of agricultural production systems, describing crop-specific environmental requirements and adaptability characteristics, including input level 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 (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.

World food system model

The world food system model comprises a series of national and regional agricultural economic models. It provides a framework for analyzing the world food system, viewing national food and agricultural components as embedded in national economies, which in turn interact 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 together by means of a world market, where international clearing prices are computed to equalize global demand with supply (see Box 1).

Simulations with the world food system model generate a variety of outputs. At the global level these include world market prices, global population, global production and consumption. At the country level it includes producer and retail prices, levels of production, use of primary production factors (land, labor, and capital), intermediate input use (feed and fertilizer), human consumption, use for biofuel production, and 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 model system. Population numbers and projected incomes are used to determine 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 U.N. data at country-level, while the rate of technical progress has been estimated from past agricultural performance.

To assess agricultural development over the next decades to 2050, it was necessary to first make some coherent assumptions about how key socio-economic drivers of food systems might evolve over that period. For the analysis reported in this paper, population projections were taken from the database of the UN World Population Prospects: The 2008 Revision (United Nations, 2009). Economic growth of countries and regional groups in the world food system model was calibrated based on information provided by the Agriculture Toward 2030/50 study group at FAO (J. Bruinsma, 2009; pers. communication).

Another external input to the model system is projected climate change, which affects region-specific crop suitability and attainable yields. This spatial agronomic information (derived from AEZ) is used in an aggregate form by the economic model 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 UK Hadley Center for Climate Prediction and Research and the Australian CSIRO were used to take into account climate change impacts on land suitability and productivity (Fischer et al., 2002b).

Box 1: **How does the world food system work?**

The world food system model is an applied general equilibrium (AGE) model system. While focusing on agriculture, this necessitates that also all other economic activities are represented in the model. Financial flows as well as commodity flows within a country and at the international level are kept consistent in the sense that they must balance, by imposing a system of budget constraints and market-clearing conditions. Whatever is produced will be demanded, either for human consumption, feed, biofuel use, or as 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.), at the national as well as the international level. 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, not more can be spent than what is earned.

Each individual model component focuses primarily on the agricultural sector, but includes also a simple representation the entire economy as necessary to capture essential dynamics among capital, labor and land. For the purpose of international linkage, production, consumption and trade of goods and services are aggregated into nine main agricultural sectors. The nine agricultural sectors include: wheat; rice; coarse grains; bovine and ovine meat; dairy products; other meat and fish; oilseed cakes and protein meals; other food; non-food agriculture. The rest of the economy is coarsely aggregated into one simplified non-agricultural sector. Agricultural commodities may be used in the model for human consumption, feed, as biofuel feedstock, for intermediate consumption, and stock accumulation. The non-agricultural commodity contributes also as investment, and as input for processing and transporting agricultural goods. All physical and financial accounts are balanced and mutually consistent: the production, consumption, and financial ones at the national level, and the 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 time period. Within each one-year time period, demand changes with price and commodity buffer stocks can be adjusted for short-term supply response. Production in the following marketing year (due to time lags in the agricultural production cycle) is affected by changes in relative prices. This feature makes the world food 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 production and income of households and governments.

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

The IIASA world food system model has been calibrated and validated over past time windows and successfully 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; Fischer et al., 1994; Rosenzweig and Parry, 1994; Fischer et al., 2002b; Fischer et al., 2005; Tubiello and Fischer, 2006).

ANNEX 2: AGGREGATION OF WORLD FOOD SYSTEM COMPONENTS TO WORLD REGIONS

Economic group	**Region**	**WFS Component**
DEVELOPED	North America	Canada, United States
	Europe & Russia	Austria, EC-9, Eastern Europe, Former USSR, Turkey
	Pacific OECD	Australia, Japan, New Zealand
DEVELOPING	Africa, sub-Saharan	Kenya, Nigeria, Africa Oil Exporters, Africa medium income/food exporters, Africa low income/food exporters, Africa low income/f exporters
	Latin America	Argentina, Brazil, Mexico, Latin America high income/food exporters, Latin America high income/food importers, Latin America medium income
	Middle East & North Africa	Egypt, Africa medium income/food importers, Near/Middle East oil exporters, Near/Middle East medium-low income countries.
	Asia, East	China, Far East Asia high-medium income/food importers
	Asia, South/Southeast	India, Pakistan, Indonesia, Thailand, Asia low income countries Far East Asia high-medium income/food exporters
REST of WORLD	Rest of World	Rest of the world

Aggregate Regional Country Group Models:

African Oil Exporters: Algeria, Angola, Congo, Gabon.
Africa, Medium Income, Food Exporters: Ghana, Cote d'Ivoire, Senegal, Cameroon, Mauritius, Zimbabwe.
Africa, Medium Income, Food Importers: Morocco, Tunisia, Liberia, Mauritania, Zambia.
Africa, Low Income, Food Exporters: Benin, Gambia, Togo, Ethiopia, Malawi, Mozambique, Uganda, Sudan.
Africa, Low Income, Food Importers: Guinea, Mali, 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, Bolivia.

South East Asia, High-Medium Income, Food Exporters: Malaysia, Philippines.
South East Asia, High-Medium Income, Food Importers: Republic of Korea, Democratic People's Republic Korea, Laos, Vietnam, Cambodia.
Asia, Low Income: Bangladesh, Myanmar, Nepal, Sri Lanka.

Near/Middle East, Oil Exporters: Libya, Iran, Iraq, Saudi Arabia, Cyprus, Lebanon, Syria.
Near/Middle East, Medium-Low Income: Jordan, Yemen, Afghanistan.

Note: The *Rest of the World* aggregate includes both more and less developed countries. Although the aggregate variables in ROW are dominated by more developed countries of the OECD, these are not included with the respective broad regional aggregates, DEVELOPED and DEVELOPING.