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Biofuel policies for dynamic markets

Impacts of biofuel expansion on world food systems and the environment

A GLOBAL AGRICULTURAL ECOLOGICAL-ECONOMIC MODELLING FRAMEWORK FOR SCENARIO ANALYSIS

Report of ELOBIO WP5:

Assessment of biofuel policy impacts in food and feed markets

Intelligent Energy Europe

Impacts of biofuel expansion on world food systems and the environment

A GLOBAL AGRICULTURAL ECOLOGICAL-ECONOMIC MODELLING FRAMEWORK FOR SCENARIO ANALYSIS

ELOBIO Deliverable 5.2 (Description and documentation of assessment model used to quantify impacts of biofuel scenarios on food and feed markets)
ELOBIO Deliverable 5.3 (Quantified impacts of alternative biofuel policies on food and feed markets)

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Executive Summary

A state-of-the-art ecological-economic modelling framework has been applied to address quantitatively and spatially explicit questions and policies raised by ELOBIO stakeholder consultations and the project team to assess the impact of biofuel expansion on world food systems and the environment.

The IIASA world food system model (WFS) is an applied general equilibrium (AGE) model system representing national and international markets with a focus on agriculture. The FAO/IIASA Agro-Ecological Zones (AEZ) model uses detailed agronomic-based knowledge to estimate crop production potentials employing detailed spatial biophysical and socio-economic datasets to distribute its computations at fined gridded intervals of 5’ by 5’ latitude/longitude over the entire globe.

Both modelling systems were extended to include major biofuel feedstocks. Full consistency, between the spatial AEZ approach used for appraising land resources and land productivity on the one hand and the expansion of cultivated land determined in the WFS on the other hand, is achieved by allocating the conversion of agricultural land to the spatial grid for 10-year time steps by solving a series of multi-criteria optimization problems for each of the countries/regions of the world food system model.

Biofuel scenarios

Storylines and quantified development scenarios were selected to inform the world food system model of demographic changes, projected economic growth, international policy settings (e.g. trade liberalization and migration), agricultural technology, climate change scenarios, land use restrictions and transport biofuel demand. Two biofuel scenarios, which represent foreseen policies for future biofuel demand, have been compared with a baseline assessment (Scenario REF) portraying a world where biofuel consumption remains at the year 2008 level of consumption.

The biofuel scenario WEO assumes until 2030 regional biofuel use as projected by World Energy Outlook Reference scenario (WEO 2008) as projected by the International Energy Agency (IEA, 2008) and second-generation conversion technologies becoming commercially available after 2015 and being deployed gradually. A target scenario *TAR* assumes a fast expansion of biofuel production in accordance with mandatory, voluntary or indicative targets announced by major developed and developing countries and an accelerated deployment of second-generation conversion technologies. Between 2030 and 2050, both biofuel scenarios assume biofuel consumption to increase linearly according to regional per capita biofuel consumptions between 2000 and 2030. The simulations were carried out on a yearly basis from 1990 to 2050.

Sensitivity runs highlight (i) the importance of animal feed generated as by-product during biofuel production; (ii) the impact of higher agricultural productivity growth; and (iii) implications of land use restrictions. The assumed additional productivity growth rates in the scenarios WEO-vP and TAR-vP depend on the countries current yield gaps with two developing country groups being defined. Group 1 includes Sub-Saharan Africa where crop yield productivity is assumed to be 7.5% and 20% higher by 2025 and 2050 respectively compared to the other scenarios. The second group assumes +4% and +10% for the same time periods and includes India and several countries in Central and South America.

Impacts on the world food system

The increased demand for food staples due to the production of first-generation biofuels results in market imbalances and pushes international prices upwards for all commodities except protein feed and livestock. Crop price increases are in the order of 10 to 20% depending on time, commodity and scenario. Price indices for aggregate agricultural production increase due to biofuels use especially in the beginning amounting to 7% for WEO and 16% for TAR in 2020. Whereas for scenario WEO these increases are relatively stable over time, price increases become lower in TAR due to employing more second-generation biofuel technologies. The extent of price effects is strongly dependent on assumed agricultural productivity growth rates.

The livestock sector is strongly linked to biofuel use because of valuable by-products being generated during biofuel production including livestock feed from starch based ethanol production (DDGS) and protein meals and cakes from crushing oilseeds for biodiesel production. These additional animal feed volumes result in about 30% lower prices for protein feed compared to the reference scenario REF without accelerated biofuel production.

Rising food commodity prices are of particular concern for low income consumers. By 2020 due to the use of first-generation biofuels in the WEO and TAR scenario, an additional 44 million and 94 million people respectively were estimated at risk of hunger. Agricultural productivity growth rates in developing countries are central for narrowing yield gaps and improving the region’s competitive position in world’s agricultural markets. After 2030, the anticipated additional productivity growth rates in the scenarios WEO-vP and TAR-vP are sufficiently high to counterbalance increases in hungry people caused by biofuel expansion.

Biofuels modestly enhance rural development. Beneficiaries depend on the regions’ competitive strength. Focusing on reducing yield gaps in developing countries, as assumed in WEO-vP and TAR-vP brings about gains in value added from crop and livestock sector of up to 6%. This increased competition reduces the rural development gains from biofuel production in developed countries.

Impacts on the environment

First-generation biofuel consumption based on food and feed crops results in additional agricultural production, which is achieved by a combination of productivity increases on existing arable land and arable land expansion. Land use changes induced by increased biofuel consumption are in the centre of the debate on the benefits of biofuels for climate change and greenhouse gas saving, a prime goal of biofuel use. This study captures both direct and indirect land use changes by modelling responses of consumers and producers to price changes induced by competition of traditional food and feed markets with biofuel feedstock production.

Due to first-generation biofuel feedstock production by 2030 an additional 11 and 22 million hectares would be converted to arable land in the WEO and TAR scenario respectively. This represents a net increase in arable land expansion of 9% and 18% in addition to the 120 and 170 million arable land expansion due to food and feed demand alone. More than two thirds of the additional arable land expansion occurs in Africa and Latin America. Because DDGS is used as animal feed some 7 million hectares of arable land can be used for other purposes than growing feed crops. Thus major land conversion is avoided through DDGS use, an important improvement for the biofuels greenhouse gas balances.

Land conversions can be limited by increasing yields on existing arable land. In the longer term (after 2030) the assumed agricultural productivity increases in WEO-vP and TAR-vP are sufficiently high to allow the food, feed and biofuel demand being produced primarily on existing agricultural land and thus avoiding deforestation and other land use conversions.

Extent and type of land conversions combined with the share of second-generation biofuels are the key determinants for the development of the biofuel scenarios net greenhouse gas balance over time. For the assessed biofuel scenarios the cumulative net GHG balances are positive only after 2020, i.e. only then the adoption of biofuels (as specified in the scenarios) becomes environmentally friendly in terms of lower GHG emissions compared to the fossil fuels they replace.

GHG savings are generally higher for the scenarios with higher crop productivity due to their lower arable land requirements and less land use conversion. By 2050 a maximum accumulated net GHG savings of some 25 Pg CO2 equivalent could be achieved in the TAR-vP scenario.

In terms of land use conversions and GHG savings the scenarios with higher agricultural productivity growth clearly outperforms in the longer term a reference scenario without biofuels. This highlights the importance of agricultural productivity growth and the time factor in assessing climate benefits of biofuels.

Conclusions

Biofuel consumption pushes crop prices up but animal feed prices down. Biofuel by-products use as animal feed plays an important role for offsetting price increases. The livestock sector generally benefits from biofuels use. The extent of price effects is strongly dependent on assumed agricultural productivity growth rates. Risks for food security require enhanced efforts to increase agricultural productivity growth in developing countries and achieve yield gap reductions. Biofuels can enhance rural development and beneficiaries depend on the regions' competitive strength. 'Low disturbing' biofuel development requires agricultural productivity increases to exceed food, feed and biofuel demand growth. For GHG benefits to materialize, yield gap reduction in developing countries, carefully monitored speed of biofuel expansion and enforceable land use restrictions, especially avoiding deforestation, is important.

1 Introduction

1.1 Background

A prime challenge of the agricultural sector today is to provide for future demand of food, feed, fibre and bio-energy crops, while preserving environmental and nature protection concerns to achieve long-term sustainability of land and water resources. To better understand the energy-food security-environment nexus a spatially detailed understanding of alternative land use and rural development options and strategies is essential.

In the future food, feed and energy crops may compete for agricultural land causing environmental and nature protection concerns. The recent surge in biofuel development calls for integrated modelling frameworks to assessment tools to identify policy measures that are suitable for both the promotion of bio-fuels, while at the same time avoiding negative effects on food and feed commodity markets.

The current market introduction of biofuels has significant impacts on other commodity markets. The objective of the project **E**ffective and **lo**w-disturbing **bio**fuel policies (ELOBIO[1]) is to develop low-disturbing policy options, enhancing biofuels but minimising the impacts on food and feed markets, and markets of biomass for power and heat.

A key approach in ELOBIO is an iterative stakeholder-supported development of low-disturbing biofuels policies. For this purpose three stakeholder consultations reflected on existing policies, defined problems of market-disturbance and aimed at identifying criteria and key issues to be considered for an increased deployment of biofuels in the European Union. Results of the consultation were used as an input into a modelling framework assessing the impacts of accelerated biofuel deployment on food & feed markets.

This paper presents the modelling framework and its underlying data and methodologies applied in ELOBIO for the analysis of the global ecological-economic world food system (Chapter 2). The modelling framework has been applied to address quantitatively and spatially explicit questions and policies raised by the stakeholder consultations and the ELOBIO project team to assess the impact of biofuel expansion on world food systems and the environment. To this end scenarios were formulated to assess the impact of biofuels on food security and the environment.

First a baseline assessment (Chapter 3) serves as ‘neutral’ point of comparison to which alternative biofuel scenarios are compared for their impact. This reference scenario assumes historical biofuel development until 2008 and thereafter keeps biofuel feedstock demand constant at the 2008 level. Biofuel scenarios explore the impact of different levels of biofuel demand and composition (Chapter 4). In addition Chapter 5 explores selected key variables, which affect the impact assessment of the biofuel scenarios including the importance of agricultural by-products, the impact of agricultural productivity growth, and land use restrictions. Conclusions are presented in Chapter 6.

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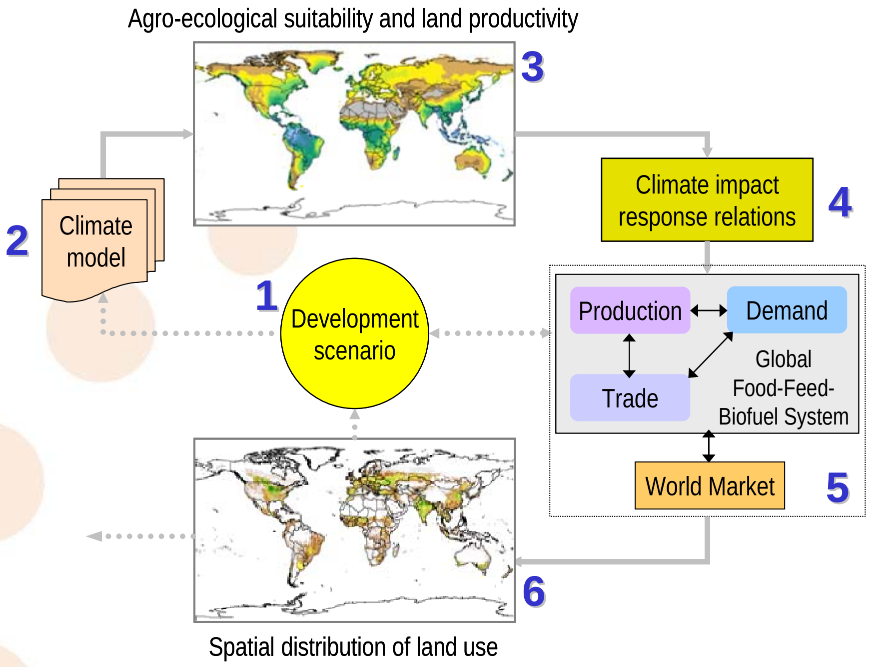
[1] For more information see: www.elobio.eu

1.2 Modelling framework

For the analysis of the global agricultural system a state-of-the-art ecological-economic modelling framework is applied. It includes as two major components, the FAO/IIASA Agro-ecological Zone (AEZ) model and the IIASA world food system (WFS) model. The two main model systems, AEZ and WFS, were adapted and expanded for resource use and by-product generation of biofuel production and form the basis of scenario evaluation and policy analysis of the impacts of increased biofuel deployment on food and agriculture at the national, regional and global levels. In addition a rule-based downscaling methodology is applied to allocate the results of the world food system simulations to the spatial grid of the resource database for the analysis and quantification of environmental implications. This modelling framework comprises six main elements, as sketched in Figure 1 and described below:

Figure 1. Framework for a global ecological-economic world food system analysis



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 defines scenarios of demand for first- and second-generation biofuels in different regions/countries. The scenario 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.
2. The emission 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 zone (AEZ) method takes as input a climate scenario and other elements from a land resources inventory including soils, landform, and present land

cover and estimates the likely agronomic impacts. The AEZ model uses detailed agronomic-based knowledge to simulate land resources availability, and assess for specified management conditions and levels of inputs, the suitability of crops in relation to both rain-fed and irrigated conditions. Relevant to specific agro-ecological contexts attainable crop production potentials are quantified for a spatial grid of 5′ by 5′ latitude/longitude (see Chapter 2).

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 (including biofuel demand) and estimated climate change yield impacts – to evaluate internally consistent world food system scenarios. It comprises a series of national and regional agricultural economic models and 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 Chapter 3).
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 (see Chapter 4.1).

1.3 Scenario approach

In the ELOBIO project the above modelling framework has been applied to study the impacts of accelerated biofuel deployment on food and feed markets and on the environment. The ELOBIO project team formulated in close collaboration with stakeholders from the biofuels industry and from industries related to markets affected by biofuel policies, scenarios and sensitivity assessments. Box 1 provides a summary of the most important scenario assumptions required for the ecological-economic modelling system.

Agricultural demand and production

To assess agricultural development over the next decades, with and without biofuel expansion, it is first necessary to make some coherent assumptions about how key socio-economic drivers of food systems might evolve over that period. On the demand side population numbers, projected incomes and potential shift in lifestyles and associated dietary changes determine demand for food for the period of study. In the current modelling framework dietary shifts are endogenous and depend on income development.

Assumptions on achievable agricultural technology and management define agricultural production potentials. Technology affects crop yield estimates and livestock productivity, by modifying the efficiency of production per given units of inputs and land. Growth in agricultural productivity is critical for the calculation of land use requirements for food, feed and biofuel feedstock production.

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).

Box 1. Scenario assumptions required for the ecological-economic modelling system assessing the impact of accelerated biofuel deployment on food and feed markets and the environment

1. Socio-economic	Population growth GDP growth Labour participation rate in agriculture
2. Agricultural technology	Crop yield growth Livestock efficiency
3. Climate change	Climate change scenarios
4. Energy and transport	Transport fuel requirements Share of biofuels in total transport fuels Biofuel portfolio (Share 1st versus 2nd generation) Biofuel feedstock selection
5. Land use restrictions	Permitted land cover conversions
6. Policy assumptions	National markets: Taxes, Subsidies International markets: Quota, tariffs, border protection

Energy and transport

For biofuel scenarios, storylines describe the extent and direction of biofuel production and use. Energy futures detail future regional transport fuel requirements, the share of biofuels in total transport fuels and future biofuel feedstock portfolios (e.g. availability of second generation technologies). Of particular importance is the assumed share of those biofuels that do not rely on conventional food and feed crops and therefore only compete for agricultural land. Finally the modelling system needs to be informed by the selection of feedstocks to satisfy a region's biofuel demand.

Land use restriction

Demand for food crops, livestock and biofuel feedstocks combined with assumed improvements in agricultural technology determine the amount of agricultural land requirements. When the existing cultivated area is insufficient to meet agricultural demand surrounding areas may be converted into agricultural productive land. Assumptions on permitted land use and land cover conversion are crucial for agricultural price calculations and environmental impacts. Expansion of agricultural land into protected areas as defined in the database on protected areas is generally not possible. For example certain land use restrictions such as no conversion of forest land to cultivated areas would have a strong effect on greenhouse gas emissions caused by direct and indirect land use conversion.

Likewise assumptions on where to grow lignocellulosic feedstocks for 2nd generation biofuels has great consequences for the competition of land used for food or energy crops.

Policy assumptions

Subsidies, taxes and boarder protection measures influence the competitive position of individual agricultural commodities in national and international markets. Likewise trade barriers for biofuels and feedstocks as well as taxes and subsidies for biofuel feedstock production affect a farmer's choice of commodity production.

2 METHODOLOGY and DATA

2.1 Assessment of land resources

2.1.1 Biofuel feedstocks

We differentiate between so-called first generation conversion, based respectively on biochemical conversion of sugar crops or crops with high starch content for bioethanol or based on vegetable oil for biodiesel, and second generation biofuels based on biochemical processes or thermo-chemical conversion using combustion, gasification and conversion of syngas, or pyrolysis.

The easiest and most efficient way to produce bioethanol is from feedstocks with high sugar content. When ethanol is produced from starch crops, an extra step is required in the conversion process to break down the starch polymers into sugar. The energy and other input requirements of this extra step in feedstock conversion negatively affects greenhouse gas balances and achievable energy input-output ratios of starch-based ethanol as compared to sugar-based ethanol. Biodiesel is produced through a well established chemical process called transesterification, which uses the vegetable oil component of feedstocks.

Second generation biofuel technologies based on lignocellulosic processing are widely regarded as the most promising route to large scale biofuel production. While first generation biofuel technologies have reached an advanced stage and are widely used in many countries, second generation technologies are still mainly applied in experimentation and demonstration projects.

Five main groups of land utilization types with specific biofuel production pathways are distinguished, namely: Sugar crops; Cereals; Oil crops; Woody plants, and herbaceous plants. The FAO/IIASA global agro-ecological zones modelling framework has been used for the assessment of production potentials of the biofuel feedstocks listed below.

(1) Sugar crops - (1st generation biofuel for production of bioethanol)

Sugar cane is a perennial crop with a C4 photosyntheic pathway, which is adapted to perform best under sunny conditions of relatively high temperatures. In temperate regions sugar beet is a widely grown crop, while sweet sorghum is regarded as a potential energy crop for the sugar to energy production pathway.

- Sugar cane *(Saccarum officinarum)*
- Sugar beet (*Beta vulgaris)*
- Sweet sorghum (*Sorghum bicolor)*

(2) Cereals - (1st generation bio-fuel for production of bioethanol)

Wheat and maize are widely grown globally, rye and triticale are (currently) much less grown but have similar potential for starch to energy conversion as wheat. Cassava is adapted to perform best in tropical lowland conditions and can be grown on soils with low fertility.

- Wheat (*Triticum aestivum*)
- Rye (*Secale cereale*)
- Triticale (*Tritico secale*)
- Maize (*Zea mays*)
- Cassava (*Manihot esculenta*)

(3) Oil crops – (1st generation biofuel for production of biodiesel)

Rapeseed and sunflower are widely grown in the temperature climates of Europe, Canada and India. Soybean’s wide climatic adaptability spectrum makes it possible for it to be grown across a range of thermal regimes, ranging from tropical to subtropical and temperate zones with warm summers, and across moisture regimes ranging from semi-arid to humid. In addition jatropha, which is today rarely used for the commercial production of vegetable oil[2], has been included in the analysis. Jatropha is reported as being a hardy, drought tolerant plant, and highly water use efficient and is therefore suggested as biofuel feedstock in marginal areas in warm semi-arid to sub-humid tropical conditions.

- Rapeseed (*Brassica napus oleifera)*
- Sunflower *(Helianthus annuus)*
- Soybean *(Glycine max)*
- Jatropha *(Jatropha curcas)*

(4) Woody plants – (2nd generation bio-fuels)

These LUTs include short rotation forestry management systems. Tree species considered include poplars, willows and eucalypts. The selected tree species cover a wide range of ecological regions of Europe.

- Poplar (*Populus nigra, Populus euramericana cv rob, Populus alba, Populus tremula, Populus balsamiferas Populus maximowiczii, Populus tomentosa, Populus euphraetica)*
- Willow (*Salix alba, Salix viminalis)*
- Eucalypt *(E. globulus, E. camaldulensis, E. viminalis)*

(5) Herbaceous lingocellulosic plants - (2nd generation bio-fuels)

The herbaceous plants selected are productive in terms of lignocellulose and cover a wide range of ecologies. Included are:

- Miscanthus (*Miscanthus sinensis*)
- Switchgrass (*Panicum virgatum*)
- Reed canary grass (*Phalaris arundinaceae*)

2.1.2 Global land resources database

A global natural resources database has been compiled for the assessment of land capabilities, productivity and constraints using most recent available geographically explicit data. The different thematic layers in the Geographic Information System (GIS) are available for a grid-cell size of 5 minutes or 30 arc seconds depending on data source.

In addition the Global Administrative Unit Layers (GAUL) map (FAO, 2009) has been transformed to the 5 minutes grid to achieve aggregation of specific information for administrative units.

Climate data and agro-climatic inventory

Historic climate

Current and historic data has been compiled using the gridded climate parameters available from East Anglia University (CRU Global climatologies) and the VASCLimO global precipitation data from the Global Precipitation Climatology Centre (GPCC).

The CRU climatologies include i) Average 1961-90 monthly variables for a 10 x 10 minutes latitude/longitude grid (CRU CL2.0, New et. al 2002); and (ii) Annual time series for a 0.5° by 0.5° latitude/longitude for monthly climatic variables (CRU TS 2.1, Mitchell and Jones

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[2] FAOSTAT reports 1.9 million hectares while other sources quote 0.9 million hectares under plantation.

2005). For the annual time series precipitation data, the VASClimO dataset from the Global Precipitation Climatology Centre was taken (Beck et.al, 2005).

Monthly climatic variables include precipitation; number of rainy days; mean minimum and mean maximum temperature; diurnal temperature range; cloudiness; wind speed; and vapour pressure.

Original climatic surfaces were interpolated to a 5 minute by 5 minute longitude/latitude grid for the average climatic data and all years between 1961 and 2002. A bilinear[3] interpolation method in an ArcGIS environment was applied. In the case of temperature a lapse rate of 0.55 degree Celsius per 100 meter elevation was applied using the digital elevation models (DEM). First, a 0.5 by 0.5 degree surface provided by CRU to calculate temperature values adjusted to sea level. Bilinear interpolation was performed for temperatures at sea level. Second, a 5 by 5 minute DEM, derived from GTOPO30, was used to calculate temperatures for actual elevations. The 5 minute DEM was compiled from GTOPO30 original 30 arc-sec elevations using the median of all 30 arc-second elevation data within each 5 minute grid cell.

Climate Change Scenarios

For the analysis of climate change impacts on agricultural production potential, available climate predictions of general circulation models (GCM) were used for characterization of future climates. The IPCC data distribution centre[4] provides future climatic parameters as a combination of socio-economic scenarios, the SRES development scenarios[5] (Nakicenovic, N. et al 2000) and climate scenarios calculated from different GCM.

The following GCMs were selected for calculation of future potential agricultural productivity:

- HadCM3 (Hadley Centre, UK Meteorological Office)
- ECHAM4 (Max-Planck-Institut for Meteorology, Germany)
- CSIRO (Australia's Commonwealth Scientific and Industrial Research Organisation, Australia)

For the spatial assessment of agronomic impacts of climate change on crop yields, climate change parameters of the respective GCM are computed for each grid cell by comparing monthly-mean prediction for three future 30 year periods (the 2020s: years 2010-2040; the 2050s: years 2040-2070; and the 2080s: years 2070-2100) to those corresponding to the GCM ‘baseline’ climate of 1960-1990. Such changes (i.e. differences for temperature; ratios for precipitation, etc.) of the centre points of each grid cell in the original GCM were first interpolated to a 0.5 degree by 0.5 degree grid using an inverse distance weighted interpolation and then applied to the observed climate of 1960-1990 to generate future climate data. Deviations in agricultural productivity as a result of climate change are calculated by running AEZ crop models for future time slots and compare results to its climatic baseline.

Agro-climatic inventory

Historic and future monthly climate surfaces are a key input for the specification of the temperature and moisture regime in a grid-cell. Monthly data are transformed into daily data using a spline interpolation and analyzed vis-à-vis crop temperature and water requirements. Reference evapotranspiration (ET_o) has been calculated according to Penman-Monteith.

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[3] Bilinear interpolation uses the value of the four nearest input cell centres to determine the value of the output raster. The new value for the output cell is a weighted average of these four values, adjusted to account for their distance from the centre of the output cell.

[4] The International Panel on Climate Change (IPCC) Data districution center: http://www.ipcc-data.org/

[5] For more information on SRES scenarios see: http://sedac.ciesin.columbia.edu/ddc/sres/index.html

Temperature and elevation are used for the characterization of thermal conditions, e.g., thermal climates, temperature growing periods, and accumulated temperatures. A water-balance model provides daily soil water balances and estimates actual evapotranspiration (ET_a) of specific crops. The temperature and moisture regime determines length of growing period, i.e. the period during the year when temperature and moisture is conducive to crop growth. This has been defined as the number of days when temperature is above 5 degree Celsius and ET_a is at least 0.4 times ET_o.

Topography

A global terrain slope and aspect database has been compiled using available high-resolution elevation data. The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (DEMs) for over 80% of the globe. The SRTM data cover globe areas up to 60° latitude and is publicly available as 3 arc second (approximately 90 meters resolution at the equator) DEMs (CGIAR-CSI, 2006). For latitudes over 60 degrees north elevation data from GTOPO30 (USGS, 2002) with a resolution of 30 arc-seconds (depending on latitude this is approximately a 1 by 1 km cell size) were used.

The high resolution SRTM data have been used for calculating[6]:

1. Terrain slope gradients and classes for each 3 arc-sec grid cell;
2. Aspect of terrain slopes for each 3 arc-sec grid cell;
3. Distributions of slope gradient and slope aspect classes for 30 arc second grid.

A global terrain slope and aspect database comprises the following elements.

- Elevation (median)
- Slope gradient: Distributions of nine slope gradient classes are available for each grid-cell: 0–0.5%, 0.5–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and > 45%.
- Slope aspects: Slope aspect data is stored in distributions of five classes namely: Class 1: slopes below 2% undefined aspect; Class 2: slopes facing North (315°–45°); Class 3: East (45°–135°); Class 4: South (135°–225°), and Class 5: West (225°–315°).

Soil database

Spatial soil information and attributes data is used from the recently published Harmonized World Soil Database (HWSD) (FAO, IIASA, ISRIC, ISSCAS & JRC, 2008). Four source databases were used to compile version 1.0 of the HWSD: the European Soil Database (ESDB), the 1:1 million soil map of China, various regional SOTER databases (SOTWIS Database), and the Soil Map of the World.

The HWSD is composed of a GIS raster image file linked to an attribute database in Microsoft Access format. The spatial resolution is about 1 km (30 arc seconds by 30 arc seconds). For the globe the database consists of 21600 rows and 43200 columns, of which 221 million grid cells cover the globe's land territory.

Over 16000 different soil mapping units are recognized in the Harmonized World Soil Database (HWSD), which are linked to harmonized attribute data. Use of a standardized

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[6] For a detailed description of the calculation procedures see: http://www.iiasa.ac.at/Research/LUC/luc07/External-World-soil-database/HTML/global-terrain-doc.html

structure allows linkage of the attribute data with GIS to display or query the composition in terms of soil units and the characterization of selected soil parameters (organic Carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry).

The derived soil properties presented with the HWSD have been derived from analyzed profile data obtained from a wide range of countries and sources. A main data source was the World Inventory of Soil Emission Potential (WISE) database comprising 9607 profiles. It has been used to derive topsoil and subsoil parameters using uniform taxonomy-based pedotransfer (taxotransfer) rules (Batjes et al, 1997; Batjes, 2002). Similarly, soil parameter estimates for all secondary SOTER databases (SOTWIS) were derived using consistent procedures as detailed in Batjes et al. (2007) and Van Engelen et al. (2005).

Land cover / land use

The following geographic datasets were used for the compilation of an inventory of seven major land cover/land use categories at 5' resolution. The datasets used are:

1. GLC2000 land cover database at 30 arc-sec[7], using regional and global legends;
2. an IFPRI global land cover categorization providing 17 land cover classes at 30 arc-sec. (IFPRI, 2002), based on a reinterpretation of the Global Land Cover Characteristics Database (GLCC ver. 2.0), EROS Data Centre (EDC, 2000);
3. FAO's Global Forest Resources Assessment 2000 (FAO, 2001) at 30 arc-sec. resolution;
4. digital Global Map of Irrigated Areas (GMIA) version 4.0 of (FAO/University of Frankfurt) at 5' by 5' latitude/longitude resolution, providing by grid-cell the percentage land area equipped with irrigation infrastructure;
5. IUCN-WCMC protected areas inventory at 30-arc-seconds[8], and
6. a spatial population density inventory (30-arc seconds) for year 2000 developed by FAO-SDRN, based on spatial data of LANDSCAN 2003[9], with calibration to UN 2000 population figures.

An iterative calculation procedure has been implemented to estimate land cover class weights, consistent with aggregate FAO land statistics and spatial land cover patterns obtained from (the above mentioned) remotely sensed data, allowing the quantification of major land use/land cover shares in individual 5' by 5' latitude/longitude grid cells. The estimated class weights define for each land cover class the presence of respectively cultivated land and forest. Starting values of class weights used in the iterative procedure were obtained by cross-country regression of statistical data of cultivated and forest land against land cover class distributions obtained from GIS, aggregated to national level.

The percentage of urban/built-up land in a grid-cell was estimated based on presence of respective land cover classes as well as regression equations relating built-up land with number of people and population density.

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[7] http://www-gvm.jrc.it/glc2000
[8] http://www.unep-wcmc.org/wdpa/index.htm
[9] http://www.ornl.gov/sci/landscan/landscanCommon/landscan03_release.html

Remaining areas were allocated to:

1. grassland and other vegetated areas (excluding cultivated land and forest);
2. barren or very sparsely vegetated areas, and
3. water bodies

according to indicated land cover classes. Barren or very sparsely vegetated areas (class (1 above) were delineated from (2) using the respective land cover information in GLC 2000 and a minimum bio-productivity threshold. The resulting seven land use land cover categories shares are:

1. Rain-fed cultivated land;
2. Irrigated cultivated land;
3. Forest;
4. Pastures and other vegetated land;
5. Barren and very sparsely vegetated land;
6. Water; and
7. Urban land and land required for housing and infrastructure.

The estimation procedures for estimating seven major land-use and land cover categories are as follows: Cultivated land shares in individual 5' grid cells were estimated with data from several land cover datasets:

(i) the GLC2000 land cover regional and global classifications at 30-arc-sec[10]
(ii) the global land cover categorization, compiled by IFPRI (IFPRI, 2002), based on a reinterpretation of the Global Land Cover Characteristics Database (GLCC) version 2.0, EROS Data Center (EDC, 2000)
(iii) the Forest Resources Assessment (FRA) of FAO (FAO, 2001a),
(iv) global 5' inventories of irrigated land (GMIA version 4.0; FAO/University of Frankfurt, 2006).

Interpretations of these land cover data sets have been used together with statistical data from the FAO for the base year 2000 to derive a consistent spatial characterization of each land unit (at 5′ by 5′ latitude/longitude grid-cells) in terms of area shares for seven main land use/land cover classes.

1. cultivated land rain-fed
2. cultivated land irrigated
3. forest
4. pasture and other vegetation
5. barren and very sparsely vegetated land
6. water
7. urban land and land required for housing and infrastructure

Total cultivated land in a country corresponds with FAO's agricultural statistics and forest land with results published in the FRA.

Land cover interpretations have been used for the base year 2000 together with statistical data from the FAO to derive a consistent spatial characterization of each land unit (at 5′ by 5′ latitude/longitude grid-cells) in terms of area shares for seven main land use/land cover

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[10] http://www-gvm.jrc.it/glc2000

classes. These shares are: cultivated land, subdivided into (i) rain-fed and (ii) irrigated land, (iii) forest, (iv) pasture and other vegetation, (v) barren and very sparsely vegetated land, (vi) water, and (vii) urban land and land required for housing and infrastructure.

Potential yields, suitable areas and production were quantified for different major current land cover categories (Fischer et al., 2008a).

Protected areas

The World Database of Protected Areas Annual Release 2009 (henceforth WDPA2009[11]) and for the territory of the European Union the NATURA 2000 network, were applied to identify two main categories of protected areas, which are distinguished and used in the GAEZ analysis:

1. Protected areas where restricted agricultural use is permitted
2. Strictly protected areas where agricultural use is not permitted

The WDPA2009 includes point and polygon data. The global database of the latter was used for identification of protected and strictly protected areas. WDPA2009 identifies 80,142 different mapping units (termed “Site-ids”) with associated attribute data for over 450,000 polygons. The majority of mapping units (51,556) recognizes either an international or national convention.

The remaining mapping units record at least the type of protected area in English, e.g. national park, natural monument (item DESIG_ENG in WDPA2009). From those 77 different designations were assigned to the strictly protected area category because their name indicates areas where agricultural use is very likely not permitted. Designations with the largest area coverage include ‘National Parks’, ‘Forest Reserves’, ‘Zapovednik’ (a protected area in Russia which is kept "forever wild"), ‘Wildlife Management Area’, ‘Nature Park’, ‘Resource Reserve’, ‘Nature Reserve’, and ‘Game Reserve’.

WDPA2009 protected areas inventory were converted to a 30 arc-seconds grid layer, which identifies over 23 million grid-cells as strictly protected and 6.8 million grid-cells as protected areas. Investigating the European part of the WDPA inventory reveals that important protected areas for the EU 27 are not included, which are however part of the NATURA 2000 network. This network of nature protection areas aims to assure the long-term survival of Europe's most valuable and threatened species and habitats and fulfills an obligation under the UN Convention on Biological Diversity. NATURA 2000 currently includes over 26,000 protected areas covering a total area of around 850,000 km^2, representing more than 20% of total EU territory.

To distinguish ‘protected’ and ‘strictly protected’ areas Corine land cover 2000 (CLC2000[12]) resolution and categorized using the 44 land cover classes of the 3-level Corine nomenclature. The spatial polygon database of NATURA 2000 was converted to a 100 m grid-cell size and overlaid with CLC2000. The Corine land cover classes ‘Arable land’, ‘Permanent crops’ and ‘Heterogeneous agriculture’ were assigned to the ‘protected areas’ category, thus permitting restricted agricultural use. Occurrence of NATURA 2000 sites in the remaining land cover classes were considered to represent ‘strictly protected areas’, where cultivation of arable crops is not possible.

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[11] Available at: http://www.wdpa.org/AnnualRelease.aspx

[12] Available at: http://etc-lusi.eionet.europa.eu/CLC2000/

The 100 meters resolution grid map showing the two types of protected areas was projected to a 30 arc second longitude/latitude grid map and the areas of the 27 countries of the European Union (EU27) was integrated in the GAEZ 2009 protected areas layer.

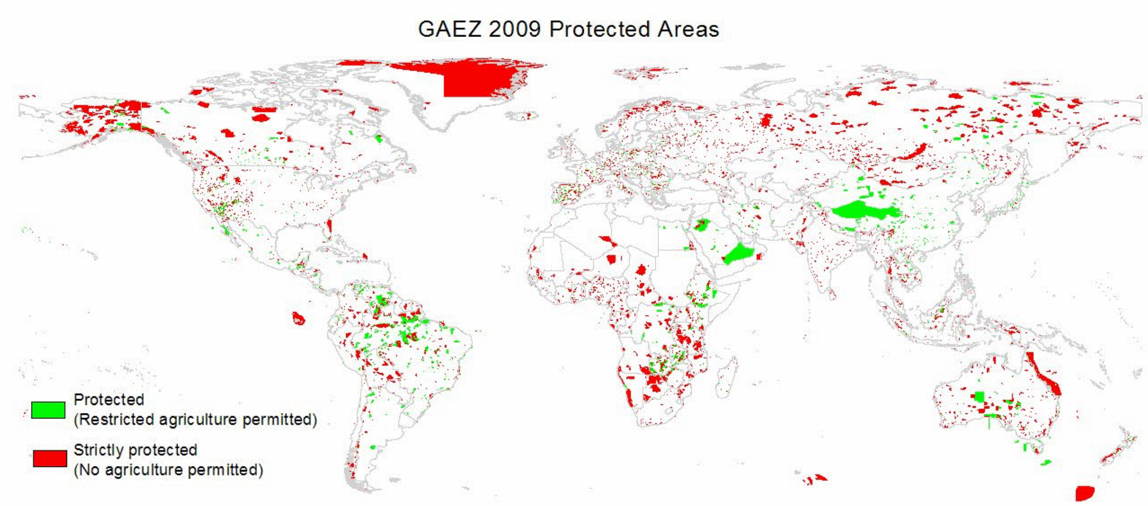
Table 1 presents a comprehensive summary of the various convention types used in the GAEZ protected areas layer, which in turn are divided in types which permit or do not permit agricultural use. The 30 arc-second GIS layer of protected areas comprises of almost 31 thousand grid cells, of which 80% are considered as 'strictly protected areas' and the remainder as 'protected areas' (Figure 2).

Table 1. Agricultural use restrictions applied to convention types used in GAEZ 2009

	Agricultural use
CONVENTION TYPES **INTERNATIONAL** (Source WDPA2009)	
Ramsar[1] (Wetlands) Convention	no
World Heritage Convention	no
UNESCO-MAB[2] Biosphere Reserves	no
ASEAN Heritage - Conservation areas in the ASEAN countries	no
CONVENTION TYPES **NATIONAL** (Source WDPA2009)	
IUCN[3] Ia Strict Nature Reserve (protected for science)	no
IUCN Ib Wilderness Area	no
IUCN II National Park (ecosystem conservation & recreation)	no
IUCN III Natural Monument (conservation of specific natural features)	no
IUCN IV Habitat/Species Management Area	no
IUCN V Protected Landscape/Seascape	yes
IUCN VI Managed Resource Protected Area	yes
Item DESIG_ENG in WDPA2009 indicates strict nature protection (own interpretation)	
Non-forest habitat	no
Forest habitat	no
NATURA 2000 (Source NATURA 2000 and CLC2000) applies only in European Union	
Natura 2000 with restricted agricultural use – Natura 2000 occurring in CLC land cover classes Arable land, Permanent crops and Heterogeneous agriculture	yes
Natura 2000 strict protection – Natura 2000 occurring in all CLC classes, except arable land, permanent crops, heterogeneous agriculture	no

1 Ramsar: http://www.ramsar.org ; 2 UNESCO-MAB http://www.unesco.org/mab ;
3 see also: http://www.unep-wcmc.org/protected_areas/categories/eng/

Figure 2. GAEZ 2009 layer of protected areas



2.1.3 Agro-ecological zones (AEZ) methodology

The AEZ modelling uses detailed agronomic-based knowledge to simulate land resources availability, assess farm-level management options and estimate crop production potentials. It employs detailed spatial biophysical and socio-economic datasets to distribute its computations at fine gridded intervals over the entire globe. The AEZ global assessment includes 2.2 million land grid cells at 5′ by 5′ latitude/longitude (Fischer et.al 2002a,b and 2008). A 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 modelling and environmental matching procedures are used to identify crop-specific environmental limitations, under various levels of inputs and management conditions. For bioenergy assessments a companion model of AEZ has been developed that enables assessments of potential productivity of tree species as well (Fisher et.al 2005).

Figure 3 presents a schematic overview of the flow and integration as implemented.

Feedstock land utilization definition: The AEZ procedures have been used to derive, by grid-cell, potential biomass and yield estimates for rain-fed biofuel feedstock production under a high level of inputs/advanced management, which includes the main socio-economic and agronomic/farm-management components: The farming system is (i) market oriented; (ii) commercial production of biofuel feedstocks are management objectives, and (iii) production is based on currently available yielding cultivars, is fully mechanized with low labor intensity, and assumes adequate applications of nutrients and chemical pest, disease and weed control.

The quantified description of biofuel feedstock land utilization types (LUT) include characteristics such as vegetation period, ratoon practices, photosynthetic pathway, photosynthesis in relation to temperature, maximum leaf area index, partitioning coefficients, and parameters describing ecological requirements of biofuel feedstock produced under rain-fed conditions.

Climate analysis: The climatic data comprise precipitation, temperature, wind speed, sunshine hours and relative humidity, which are converted in an agronomically meaningful climate resources inventory describing in space and time quantified thermal and soil moisture regimes. The latter includes daily soil water balances and calculation of potential and actual evapotranspiration, and length of growing period parameters, including year-to-year variability.

Land resources database: described in Section 2.2.

Biomass and yield potentials: Several calculations and matching procedures are applied on the grid cell level to determine potential yields for each crop/LUT. The basic idea here is to test the growth requirement of the crops against a very detailed set of agro-climatic and soil conditions derived from the land resources database. In a stepwise procedure first thermal and radiation conditions and second moisture supply conditions in each grid cell are compared with the requirements of a particular crop/LUT. The edaphic suitability assessment matches soil and terrain requirements of the assumed LUT with prevailing soil and terrain conditions. Empirical reduction ratings are applied to reduce yields for agro-climatic constraints (e.g. effects of pests and diseases, year-to-year variability in soil moisture balance, workability constraints). Finally yield reduction due to soil and terrain limitations are accounted for. Soil suitability is evaluated on the basis of the soil attribute of the Harmonized World Soil Database. The combination of soil and terrain data provides a terrain-slope suitability rating.

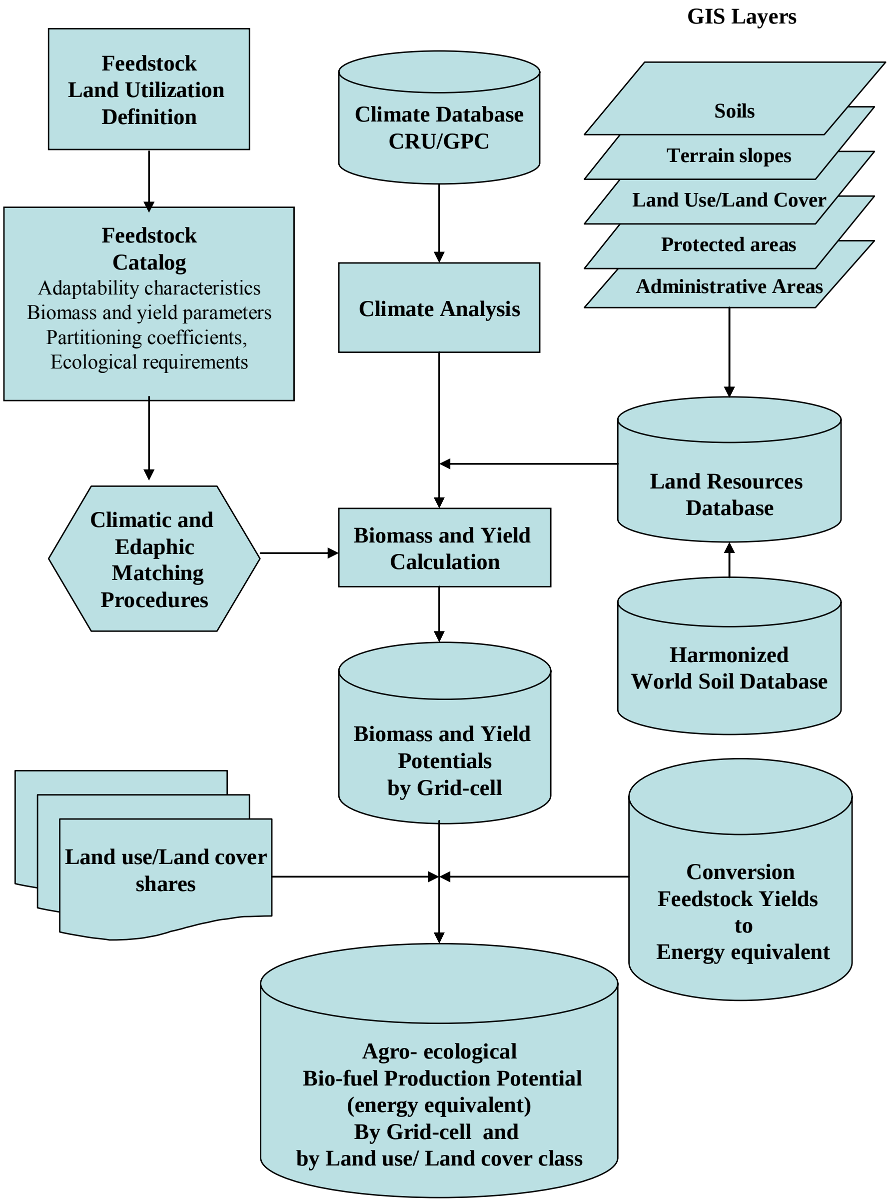
It is used to define permissible slope ranges for cultivation of crop/LUTs under certain farming practices and thereby achieve production sustainability by avoiding topsoil erosion.

The combination of the climatic and edaphic suitability classification provides by grid-cell potential biomass and yield estimates for assumed production conditions.

Biofuel production (in energy equivalents): By applying published conversion factors biomass yields were transferred into biofuel energy equivalents.

Land use/Land cover shares are used to evaluate biofuel feedstock production and energy yield potentials by grid-cell and land cover type.

Figure 3. AEZ methodology – Information Flow and Integration



2.2 The World Food System Model

2.2.1 World agricultural trade and economic modelling

The IIASA world food system model (WFS) is an applied general equilibrium (AGE) model system. While focusing on agriculture, all other economic activities are also represented. 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.

There are three groups of actors with each country/region: (i) *producers*, who supply commodities and demand inputs including primary factors; (ii) *consumers* who demand commodities and supply primary factors; and (iii) *government*, which sets taxes, subsidies, and quotas, and otherwise intervenes in the market. Each group is constrained – producers by technology, consumers and government by their budgets – and it is assumed that the agents are rational and maximize their objectives.

Consistency of financial flows is imposed at the level of the economic agents in the model (individual income groups including 'household agriculture' and 'household non-agriculture', 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.

A series of national and regional agricultural economic models provide 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. WFS consists of 21 national and 13 regional geographical components (Annex 1) covering the world. The national models cover more than 80% of the world's food attributes, such as population, land, demand, production, trade, etc. The individual national/regional models are linked together by means of a world market[13], where international clearing prices are computed to equalize global demand with supply.

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, labour 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:

(1) Wheat; (2) Rice; (3) Coarse grains; (4) Bovine and ovine meat; (5) Dairy products; (6) Other meat and fish; (7) Oilseed cakes and protein meals; (8) Other food; and (9) *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:

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[13] Exchange rates are kept constant over time because WFS does not include a money market.

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, see Section 2.1) 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.

Assumptions on population growth, economic growth and technology provide key external inputs to WFS. Population numbers and projected incomes are used to determine future food demand. Technology affects crop and livestock productivity estimates by modifying the efficiency of production per given units of inputs.

Another key external input is climate and environment derived from AEZ calculations, which determine crop suitability and potential yields used by the economic model as an input in resource allocation. Thus projected climate changes affect WFS results.

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.

The IIASA WFS and its predecessor the IIASA Basic Linked System (BLS) have 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).

2.2.2 Specifications for biofuels

First generation biofuel feedstocks are based on conventional agricultural crops (sugar cane, maize, oilseeds, palm oil, etc.) and thus increased production of biofuel feedstocks adds to a country's demand for those crops in addition to their food and feed demand. Exogenous biofuel demand and biofuel portfolios, as derived from different energy scenarios, determine the amount of conventional crops required for production in a country.

The use of feedstocks to achieve first generation biofuel production levels depends on the type of biofuel (bioethanol or biodiesel) and the country or region. The various possible feedstocks are grouped and compete amongst each other.

Biofuel feedstocks produce not only the ingredients required for biofuel production but often generate by-products. Depending on type of feedstock, conversion technology as well as which parts of the plants are used in biofuel production, substantial amounts of by-products may be produced. By-products include valuable animal feed. They may either substitute imports of feed or compete with conventional domestic feed sources. In such case both trade and domestic feed markets may be strongly affected.

The animal feed industry has productively utilized the by-products associated with the refining of oilseeds into higher value food material and more recently into biodiesel. In the case of soybean, the soymeal by-product is usually the prime reason for soybean production.

The alcohol-free solids and liquids remaining after fermentation and distillation of sugar to ethanol are generally recombined for sale as high-protein animal feed. In its wet form they are known as wet distillers grains with solubles (WDGS) and can be sold to nearby markets. When they are dried their shelf life is extended and they are sold on domestic markets or exported as dried distillers grains with solubles (DDGS).

For every ton of ethanol produced from starchy crops, a ton of DDGS is produced. It is assumed that all DDGS produced will enter commodity markets and will be used as animal feed.

Depending on feedstock, biofuels and their by-products directly impact the following agricultural sectors represented in WFS.

Sector I – Wheat (includes biofuel feedstocks wheat)

Sector III – Coarse Grains (includes maize)

Sector VII – Oilcakes and protein meals (by-product of oilseed production)

Sector VIII – Other food (includes sugar, cassava, oil)

To quantify impacts of biofuel production and use on main agricultural commodity and factor markets results are presented relative to current and projected reference conditions, i.e. without consideration of biofuel promotion. Resource use and by-product generation of biofuel production results in altered commodity exchanges and prices. The difference between reference and biofuel scenarios can be computed with regards to impacts for food/feed markets, possible disturbances of agricultural input factor markets, and outcomes in terms of environmental impacts indicators (e.g. fertilizer use, cultivated land expansion).

Agricultural-economic assessment of accelerated biofuel feedstock production

A key objective of the ELOBIO project is to assess the relations between biofuels policies and the food and feed markets. The WFS system generates several variables relevant for an agricultural-economic assessment of accelerated biofuel feedstock production.

Commodity production: Enhanced competition for resources increases prices in factor markets and thereby may alter production costs and the competitive position of food and feed commodities. The WFS was used to calculate relative increases or decreases of food and feed commodities compared to a base case with no biofuel feedstock production. First generation biofuel feedstocks have an effect on cereals markets including regional distribution of cereal production and potential changes in trade patterns are of interest. Substantial amounts of by-products may be produced, e.g. oil cakes as a by-product of vegetable oil and biodiesel production. By-products may either substitute imports of feed or compete with conventional domestic feed sources and both trade and domestic feed markets may be strongly affected.

Price effects: In the WFS model, when simulating scenarios with increased demand for food staples caused by the production of first generation biofuels, the resulting market imbalances affect international prices. These price effects are computed over time for different food and feed commodities at the country and regional aggregates represented in WFS.

Rural development: Effects on rural income and potential changes in food security are assessed, which reflect in a broader sense rural development. Biofuels development has been seen as a means to diversify agricultural production. WFS can estimate to what extent an additional production of crops developed on arable land as feedstock for biofuels production will increase value added in agriculture.

Commodity consumption: Increased production of feedstocks for biofuels affects relative prices and incomes, which in turn result in changes in consumption of agricultural commodities. Impacts differ for non-agricultural population and agricultural population. Ambitious biofuel targets may cause higher commodity prices if achieved mainly by production of 1st generation biofuels. Consequently this reduces food consumption especially of the non-agricultural population in developing countries.

Food security: The food crop based biofuels of current production pathways are of concern as their development may exacerbate food insecurity particularly in many of developing countries. The food-feed-fuel competition for land and water resources has been a key element in debates on the impact of increased biofuel deployment on food security. The WFS computes the number of *people at risk of hunger* based on a strong empirical correlation between the shares of undernourished[14] in the total population and the ratio of average national food supply, including imports, relative to aggregate national food requirements. Details of this correlation are described in *FAO, 2001*. For instance, the share of undernourished in total population falls below 20% when aggregate food supply exceeds aggregate national food requirements by 30%.

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[14] Undernourishment refers to the condition of people whose dietary energy consumption is continuously below a minimum dietary energy requirement for maintaining a healthy life and carrying out a light physical activity with an acceptable minimum body-weight for attained-height.

2.3 Environmental assessment

The environmental benefits of increased biofuel deployment and their contribution to sustainable development are at the core of intense debates on the advantages of using biofuels.

The following sections on land use change, greenhouse gas savings, and intensification of agricultural production discusses key elements of an environmental assessment that can be quantified using the ecological-economic assessment scheme presented in this paper. Biodiversity, another important element of an environmental assessment, is primarily discussed qualitatively.

2.3.1 Land use changes

Available scenario runs projecting world food system development (Fischer et al., 2007) indicate that global food and feed demand will require some additional land to be used for cultivation, notably in developing countries. Depending on required biofuel quantity, speed of introduction, and biofuel portfolio, additional cultivated land will be required for biofuel feedstock production. Land conversion is explicitly modelled in the integrated assessment framework (see Figure 1).

In order to achieve full consistency between the spatial agro-ecological zones approach used for appraising land resources and land productivity and the expansion of cultivated land determined in the world food system model, the conversion of agricultural land is allocated to the spatial grid for 10-year time steps by solving a series of multi-criteria optimization problems for each of the countries/regions of the world food system model.

The modelling framework ensures that best information is used to (i) characterize spatial land productivity and its current function, (ii) to inform the world food system model of physical resource availability and characteristics, and (iii) to update in regular time steps the resource base and simulated use consistent with outcomes of the world food system model.

Land cover interpretations have been used for the base year 2000 together with statistical data from the FAO to derive a consistent spatial characterization of each land unit (at 5′ by 5′ latitude/longitude grid-cells) in terms of area shares for seven main land use/land cover classes. These shares are: cultivated land, subdivided into (i) rain-fed and (ii) irrigated land, (iii) forest, (iv) pasture and other vegetation, (v) barren and very sparsely vegetated land, (vi) water, and (vii) urban land and land required for housing and infrastructure.

Criteria applied in the land conversion module depend on whether there is an increase of cultivated land or a decrease in the region of consideration. In the latter case the main criteria include demand for built-up land and abandonment of marginally productive cultivated land. In case of increases of cultivated land the land conversion algorithm takes land demand from the world food system equilibrium and applies various constraints and criteria, including: (i) the total amount of land converted from and to agriculture in each region of the world food system model, (ii) the quality, availability and current use of land resources in the country/regions of the world food system model, (iii) suitability of land for conversion to cropping, (iv) legal land use limitation, i.e. protection status, (iv) spatial suitability/propensity of ecosystems to be converted to agricultural land, and (v) land accessibility, i.e. in particular a grid-cell’s distance from existing agricultural activities.

To ensure comparability across scenarios this rule set and parameterization guiding land conversion have been kept the same for all scenario simulations. Expansion of cultivated land may result in conversion of one of the following land cover categories: (i) Forests, (ii) Pastures and other vegetated land; (iii) Barren and very sparsely vegetated land.

2.3.2 Greenhouse gas savings

An important reason behind the adoption of biofuels is that they are more environmentally friendly compared to fossil fuels in terms of the greenhouse gas (GHG) emission savings. Biofuels are produced from biomass and the CO2 released through their combustion matches the amount of carbon absorbed by the plants from the atmosphere through photosynthesis; hence they appear to be carbon-neutral. However, greenhouse gases are emitted at all stages, from 'cradle to grave' of the biofuels production and uses chain in the production and transportation of feedstocks, during conversion to biofuels, distribution to end user, and in final use.

Greenhouse gases can also be emitted or sequestered as a consequence of direct or indirect land-use changes when natural habitats or previously unused or differently used land is converted to production of biofuel feedstocks. Of particular concern for greenhouse gas impacts is conversion of forests or ploughing of carbon-rich soils. Furthermore, biofuel feedstock production may not directly cause problematic conversions but may displace food or feed production to environmentally sensitive areas. Carbon debts and greenhouse gas impacts associated with biofuel production are much debated and due to the complexity of the involved land use and technical conversion systems they are difficult to quantify.

In this study we apply a general equilibrium approach to capture indirect land use changes by modelling responses of consumers and producers to price changes induced by the competition of biofuel feedstock production with food and feed production. This approach not only takes into account land use changes but also considers production intensification on existing agricultural land as well as consumer responses to changing prices and availability of commodities.

For the quantification of greenhouse gas savings due to biofuel use (assuming this use will substitute for fossil transport fuels) we apply various estimates from the literature (FAO, 2008a; Fritsche & Wiegmann, 2008; Commission of the European Communities, 2008). Estimated greenhouse savings are specific to different feedstock plants; coefficients used vary from 15-40 percent savings for maize to 70-95 percent savings for ethanol produced from sugar cane.

The impact of first-generation biofuel production on land use has been quantified by comparing land use development of a particular biofuel scenario with the land use resulting in a scenario without biofuel use. Note that this comparison includes both direct and indirect land use changes. The study methodology projects spatially explicit agricultural land uses. A carbon accounting method, based on IPCC Tier 1 approaches (IPCC, 2006), was used to quantify vegetation and soil carbon pools for each scenario. While this method is consistent with the recommended approach for greenhouse gas inventories, it goes without saying that there are large uncertainties involved in estimating regional and global carbon pools. The results should be seen as indicative for the direction and magnitude of changes.

Carbon losses from vegetation and soils due to land use change occur at the time of land conversion, but greenhouse gas savings resulting from use of biofuels rather than fossil fuels accumulate only gradually over time. We therefore calculated and compared the net balance of accumulated greenhouse gas savings due to fossil fuel substitution and the cumulated carbon losses resulting from land use changes (direct and indirect) for several periods, namely for 2000-2020, 2000-2030 and 2000-2050.

2.3.3 Fertilizer use

High input agricultural production systems may be required to attain economic bioenergy yields for the first generation technology production chain (oil crops, starch crops, sugar crops). Biofuels feedstock production based on intensive use of fertilizers results in higher greenhouse gas emissions as well as a range of other environmental risks such as soil and water pollution. Potential negative environmental impacts due to high fertilizer and pesticide will require careful management including adoption of precision-farming techniques.

Intensive use of fertilizers in biofuels feedstock production results in higher greenhouse gas emissions and impacts on other environmental factors such as water pollution. The world food system model analyzes for anticipated biofuel scenarios changes in the amount of nitrogenous fertilizers applied in response to a range of assumed levels of first-generation biofuel feedstock demand.

2.3.4 Biodiversity

Sustainable biofuel production and use should include the preservation of landscapes with significant value for biodiversity. The impacts of biofuels on biodiversity depend on (i) the extent of land use change and conversion, (ii) the type of biofuels feedstocks used and (iii) the agronomic management applied. Table 2 gives an overview of potential biodiversity effects for individual biofuel feedstocks.

Conversion of natural ecosystems, especially natural forest and natural grassland, generally causes high losses of biodiversity; impacts of using abandoned or degraded agricultural land or low intensity grazing lands are relatively less. The scale of conversion in combination with large-scale mono-cropping without compensating through e.g., “habitat islands”, and “migration corridors” may have a far reaching negative impact on biodiversity.

Feedstock specific characteristics together with typical field management practices such as scale of operation, degree of mono-cropping, tillage methods, fertilization intensity, use of agro-chemicals to combat pests and diseases have various environmental implications. The use of GMO feedstocks is debated as it may potentially reduce genetic adaptive capacity, for example the ability to endure specific ecological and biophysical conditions. Some feedstocks are aggressive invasion species (in particular jatropha and reed canary grass).

Biodiversity effects can primarily be described qualitatively. The database on protected areas in the ecological-economic modelling framework described here is used as a filter for areas excluded from potential biofuel feedstock production. However it should be noted that today many landscapes of high biodiversity have not yet been designated.

Table 2. Feedstock specific biodiversity effects

Feedstock type	**Typical land converted or used**	**Environmental Problems**	**Impact on biodiversity**	**Premium for biofuel**
Oil palm	Virgin forest	Monocultures/Irreversible destruction of virgin forest (bush fires)	Very high	High oil yields
Sugar cane	Grassland/cultivated. land	Monocultures/biotech/ processing pollution	High	Efficient ethanol production
Maize	Cultivated land	Monocultures/biotech/agro chemicals/erosion	High	Agronomic easy, Low land efficiency
Cassava	Cultivated land/ grassland/forestland	Competing with use as foodcrop	Neutral	In testing stage. High expectations
Rape	Cultivated land	Monocultures/biotech/agro chemicals/erosion	High	Simple technology but low land efficiency
Soybean	Grassland/cultivated land/forestland	Monocultures/biotech/agro chemicals/erosion. Direct and indirect intrusion in bio-diverse ecosystems	Very high	Agronomic easy, Low land efficiency
Jatropha	Grassland/cultivated land	Monocultures/socio-economic and agronomic uncertainties, toxic, invasive. Not domesticated	neutral	Uncertain relative high oil yields claimed
Switchgrass	Grassland/cultivated land	Monocultures/tall/long rotations/competing with foodcrops (invasive)	Neutral to positive	2nd gen. High yields High land efficiency
Reed Canary Grass	Grassland/wetland	Monocultures/long rotations. Best on wetland, invasive forms natural monocultures	Mod.high to neutral	2nd gen Moderately high yields, high efficiency, adapted to cool/cold environments
Miscanthus	Grassland/cultivated land	Monocultures/tall/ long rotations (invasive)	Neutral positive	2nd gen High yields High land efficiency
Willow	Grassland/woodland wetland	Best on wetland/ agro-chemicals in case of SCR	Mod.high to neutral	2nd gen High yields High land efficiency
Poplar	Grassland/woodland/ cultivated land	Monocultures agro-chemicals in case of SSR or SCR (biotech- advanced hybridization)	Mod.high to neutral	2nd gen High yields High land efficiency
Eucalypt	Grassland/woodland	Monocultures/ toxic agro-chemicals in case of SCR	Mod high to neutral	2nd gen High yields High land efficiency

Source: Fischer et. al, 2009a.

3 BASELINE ASSESSMENT

The primary role of a reference scenario (REF) is to serve as “neutral” point of departure, from which various scenarios take off as variants, with the impact of 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 2050.

3.1 Baseline quantitative assumptions

Population: 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 1% 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. Details of regional groupings in the world food system model are shown in Annex 2.

Table 3. 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[15]	210	233	249	262	272	280
World	6047	6827	7582	8231	8739	9105

Source: United Nations, March 2009.

Economic growth: Economic performance in the baseline projection REF is shown in Table 4. 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).

While the recent economic growth rates of more than 8% 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.

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

Climate change: 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 CO2 (and other trace gases) levels.

The scenario REF applies the atmosphere-ocean GCM developed by the UK Hadley Center for Climate Prediction and Research HadCM3 model (Gordon et al., 2000; Pope et al.; 2000) for the IPCC SRES A2 emissions pathway (Nakicenovic et al., 2000). Results take into account effects of CO2 fertilization and quantify outcomes with full adaptation of crop types.

Table 4. Development of GDP

	GDP (billion US $ at constant 1990 prices)						Annual growth (%)	
	2000	**2010**	**2020**	**2030**	**2040**	**2050**	2000-2020	2020-2050
North America	8286	10570	12378	13703	15327	16891	2.03	1.04
Europe & Russia	7502	9487	11621	14040	16863	19835	2.21	1.80
Pacific OECD	3795	4304	4782	5176	5538	5893	1.16	0.70
Africa, sub-Saharan	238	350	531	809	1237	1894	4.11	4.33
Latin America	1450	2015	2829	4283	6308	8860	3.40	3.88
Middle East & N. Africa	597	850	1212	1773	2627	3852	3.60	3.93
Asia, East	1596	4165	8037	13106	18374	24628	8.42	3.80
Asia, South/Southeast	1255	2021	3138	4843	7293	10135	4.69	3.99
Rest of World	2418	3000	3640	4342	5103	5913	2.07	1.63
Developed	19583	24361	28781	32919	37728	42620	1.94	1.32
Developing	5135	9402	15747	24815	35838	49368	5.76	3.88
Rest of World	2418	3000	3640	4342	5103	5913	2.07	1.63
World	27136	36762	48168	62076	78669	97901	2.91	2.39

Source: IIASA world food system simulations

Agricultural productivity: In the WFS agricultural productivity is a function of fertilizer use and a technology factor with fertilizer use being endogenous and depending on demand and prices. The technology factor is exogenously determined by region and crop type with sources derived from FAO's projections and selected countries studies (esp. United States, China, India and Russia). Efficiency in livestock production (i.e. required feed per quantity of livestock product) is kept constant over time.

Agricultural policies: Further trade liberalization is assumed for the reference world with the level of protection and subsides of the base year 1990 being halved until 2020. Depending on country the transmission of changes in world prices to domestic price levels is either based on econometrically estimated price transmission functions or on fixed protection factors (for details see Appendix A2.5 in Parik et.al, 1988).

Land use restrictions: Expansion of cultivated land is not permitted in protected areas as defined in the AEZ land resources database (see Section 2.1.2). The land conversion module in the ecological-economic modelling system has been described in Section 2.3.1.

Biofuels: The baseline scenario (REF) assumes historical biofuel development unit 2008 and keeps feedstock demand constant after 2008. No second generation technology is available.

Worldwide production of biofuels has been growing rapidly over the past few years and reached 45 Mtoe in 2008. Ethanol accounts for about 80% of biofuels with sugar cane and maize as the major feedstocks. The remaining 20% are biodiesel derived from vegetable oil, produced primarily from rapeseed. Estimates for 2008 indicate that about 80-85 million tons of cereals, mainly maize in the USA, and 280 to 300 million tons of sugar cane, mainly in Brazil, were used for ethanol production. About 10 million tons of vegetable oil was used for the production of biodiesel, dominated by the EU (Fischer et.al, 2009, Fischer et.al, 2008).

3.2 Baseline results

3.2.1 Agriculture 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% annually in the period 1970 to 1990 but since then the rate of yield growth has halved.

With still considerable population growth in the reference projections cereal demand increases resulting in production increases from 2.1 billion tons in 2000 to 3.0 billion tons in 2030, and 3.4 billion tons in 2050 (Table 5). While developing countries produced about half the global cereal harvest in 2000, their share in total production increases steadily, reaching 56 percent by 2050.

Table 5. Total cereal production and consumption, Scenario *REF*

REF	Cereal production (million tons)				Cereal consumption (million tons)			
	2000	**2020**	**2030**	**2050**	**2000**	**2020**	**2030**	**2050**
North America	477	637	669	719	318	424	443	473
Europe & Russia	530	566	595	672	545	597	625	686
Pacific OECD	40	49	51	62	45	49	50	50
Africa, sub-Saharan	75	134	174	259	106	178	231	344
Latin America	130	202	235	291	138	195	226	271
Middle East & N. Africa	55	83	96	125	98	147	178	232
Asia, East	423	528	574	650	461	573	621	679
Asia, South/Southeast	346	448	492	556	340	450	486	564
Rest of World	75	93	102	122	103	122	130	148
Developed	1014	1212	1275	1405	872	1019	1063	1140
Developing	1061	1433	1612	1930	1180	1593	1798	2159
Rest of World	75	93	102	122	103	122	130	148
World	2151	2737	2988	3456	2155	2734	2991	3446

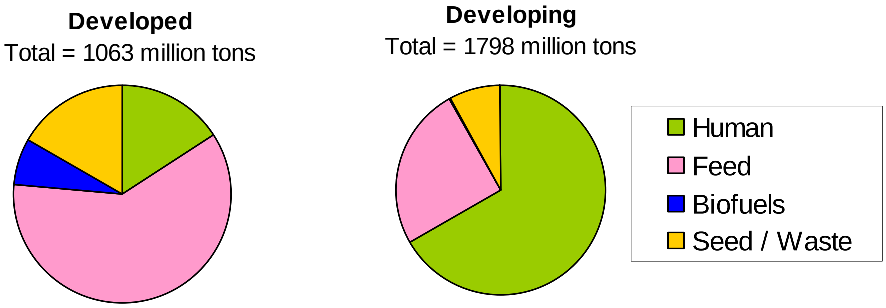
Source: IIASA world food system simulations; scenario ELOBIO-REF.

As the share of developing countries in global consumption increases from 55 percent in 2000 to 63 percent in 2050 and production increases are not large enough to compensate increased demand, net imports of cereals by developing countries are growing over time, from 120 million tons in 2000 to about 187 million tons in 2030, and some 229 million tons by 2050. North America's is by far the largest exporter of cereals with about a third of its production being exported to the world market.

At the global level total cereal consumption comprises of 47% human food use, 39% animal feed, 3.1% biofuels and the remainder is seed and waste with this composition remaining fairly constant over time. However there are large differences in cereal use between developed and developing countries (Figure 4). While in the developed world the majority of cereals is used for livestock feed (60%), in the developing world the main use is for direct human consumption (66%) and only 26% are used for livestock feed.

In developed countries the use of cereals for biofuels amounts to 7.8% in 2010 and decreases to 6.6% in 2050 in the reference scenario, which assumes no accelerated biofuel consumption after 2008. In contrast the use of biofuels is negligible in developing countries.

Figure 4. Composition of cereal consumption in 2030 for developed and developing countries, Reference Scenario



Source: IIASA world food system simulations; scenario ELOBIO-REF.

3.2.2 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% 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 REF is characterized by modest increases of world market prices during 2000 to 2050. Table 6 shows projected price indexes for crops and livestock products in comparison to 1990 levels. In part, this is also the outcome of an assumed further reduction of agricultural support and protection measures.[16]

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[16] 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.

Table 6. Agricultural prices, scenario *REF*

	Price Index (1990=100)			
Commodity group	**2020**	**2030**	**2040**	**2050**
Crops	93	98	104	111
Cereals	105	108	114	126
Other crops	87	92	99	104
Livestock products	105	108	114	117
Agriculture	96	101	106	113
Wheat	114	119	126	146
Rice	96	99	103	105
Coarse grains	107	109	116	128
Bov & Ovine	106	110	117	124
Dairy	105	109	116	119
Other meat	106	109	112	116
Protein feed	116	120	127	143

Source: IIASA world food system simulations; scenario REF.

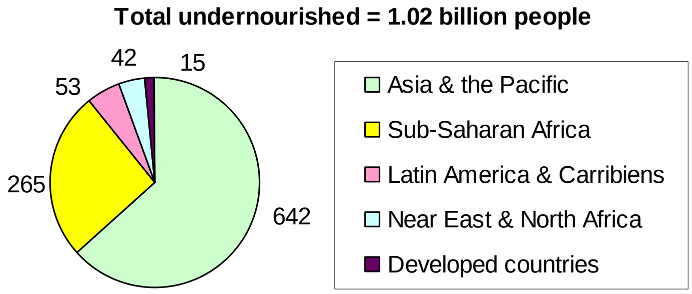
3.2.3 Risk of hunger

In 1970, 940 million people in developing countries, a third of the population, were regarded as chronically undernourished[17]. 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% of the total population compared to about 14% of the total population of the rest of the developing world.

The number of hungry/undernourished people increased between 1995–97 and 2004–06 in all regions except Latin America and the Caribbean. After the world economic crisis FAO estimates for 2009 project the number of undernourished in the world to rise to 1.02 billion people (Figure 5).

Figure 5. Undernourishment in 2009 by region (in million)



Source: FAO, 2009

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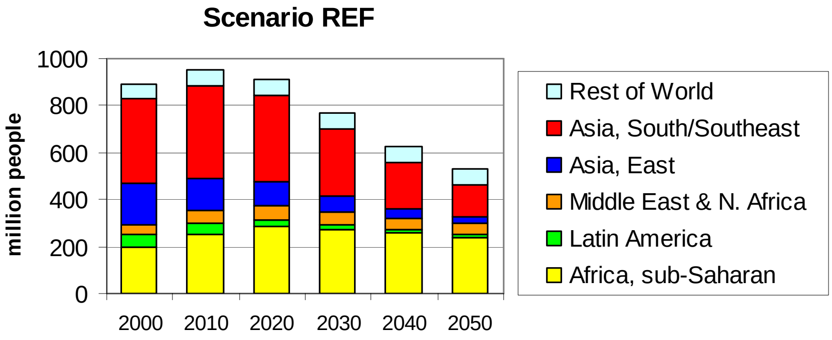
[17] Undernourishment exisits when caloric intake is below the minimum dietary energy requirement MDER). The MDER is the amount of energy needed for light activity and a minimum acceptable with for attained height, and it varies by country and from year to year depending on gender and age structure of the population.

The *REF* scenario projects globally a decreasing number of people at risk of hunger after a peak of 951 million in 2010 down to 531 million in 2050 (Figure 6). 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 in 2030 in 35 percent of the total number of people at risk of hunger to originate from Africa, and 45 percent in 2050. While achieving some progress in mitigating hunger, the projected development in this reference scenario *REF* is far from being sufficient to meet the reductions necessary to achieve the Millennium Development Goal.

Figure 6. Risk of hunger, Scenario *REF*



Source: IIASA world food system simulations; scenario REF.

3.2.4 Value added of crop and livestock production

In the scenario *REF*, the global value added of crop and livestock production in 2000 amounts to US1990$ 1262 billion. This is projected to increase by 40 percent in the 30-year period to 2030, i.e. an annual increase of 1.3%. After 2030 growth is slowing down to annual increases of 0.9%. Growth rates in developing countries are more than twice compared to those in the developed world (Table 7). Nevertheless in relation to population the developing world's contribution to global value added of the crop and livestock sector remains small. The share of the developing world is only some 60% in 2000 and increases to 70% in 2050, while 80% of world population in the year 2000 and 84% in 2050 is from developing countries.

The right part of Table 7 highlights the development of percentage of agriculture in total GDP, which decreases on a global level from 4.7% in 2000 to 2.3% in 2050. Scenario REF projects a strong decline of agriculture contribution to total GDP in the developing world from 15% in 2000 to only 3.1% in 2050.

Table 7. Value added of crop and livestock sector and percentage of agriculture in total GDP, scenario *REF*

	Billion US$ 1990			**Annual increase (%)**		**Percentage of agriculture in total GDP (%)**		
	2000	2030	2050	2000-2030	2030-2050	2000	2030	2050
North America	168	210	231	0.75	0.47	2.0	1.5	1.4
Europe & Russia	207	251	267	0.64	0.32	2.8	1.8	1.4
Pacific OECD	47	62	72	0.94	0.77	1.2	1.2	1.2
Africa, sub-Saharan	65	135	198	2.49	1.94	27.2	16.6	10.5
Latin America	155	269	319	1.84	0.86	10.7	6.2	3.6
Middle East & N. Africa	54	103	141	2.16	1.58	9.1	5.9	3.7
Asia, East	249	343	389	1.07	0.62	15.6	2.6	1.6
Asia, South/Southeast	252	403	500	1.58	1.08	20.1	8.3	4.9
Rest of World	64	84	99	0.91	0.81	2.7	2.0	1.7
Developed	422	523	570	0.72	0.43	2.2	1.6	1.3
Developing	776	1253	1547	1.61	1.06	15.1	5.0	3.1
Rest of World	64	84	99	0.91	0.81	2.7	2.0	1.7
World	1262	1861	2216	1.30	0.88	4.7	3.0	2.3

Source: IIASA world food system simulations; scenario ELOBIO-REF

3.2.5 Cultivated land use and harvested area

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 predominately 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 REF baseline scenario increases by about 168 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 8).

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 is shown in the right part of Table 8. The implied cropping intensity (defined as the ratio of arable and harvested area) increases from about 84 percent in 2000 to 89 percent in 2030, and to 92 percent in 2050. However there are strong regional differences between the developing and the developed world. Cropping intensity in developing countries is substantially higher than those in the developed countries. For example in 2030 cropping intensity is 75% in the developed world compared to 98% in the developing world.

Table 8. Cultivated land and harvested area, Scenario *REF*

	Million hectares					
Scenario REF	**Cultivated land**			**Harvested area**		
	2000	**2030**	**2050**	**2000**	**2030**	**2050**
North America	234	238	244	197	219	232
Europe & Russia	340	336	335	216	220	224
Pacific OECD	57	57	62	25	28	32
Africa, sub-Saharan	225	285	314	133	195	229
Latin America	175	219	226	127	173	183
Middle East & N. Africa	67	72	74	42	53	58
Asia, East	147	146	145	220	231	234
Asia, South/Southeast	274	289	294	313	351	360
Rest of World	42	38	36	35	34	35
Developed	605	605	612	422	451	471
Developing	915	1038	1082	850	1020	1081
Rest of World	42	38	36	35	34	35
World	1562	1681	1730	1307	1506	1586

Source: IIASA world food system simulations; scenario ELOBIO-REF.

3.2.6 Land use balances

The full integration of the land resource information (in the ecological AEZ model) and the agricultural expansion as a result of changing demand, supply and productivity (in the economic model) permits computation of land balances. Besides arable land increases, land will also be required for expanding built-up and associated areas of a growing population. Both cropland and built-up areas increase at the expense of forest and pasture and other vegetated land (details of the land conversion module are described in Section 2.3.1). Table 9 show for the reference scenario the changes in land use between 2000 and 2050. The vast majority of land use conversion occurs in developing countries with the largest changes occurring in Latin America, Sub-Saharan Africa and South / Southeast Asia.

When applying no specific land use restrictions except preserving current areas designated as protected, an estimated 99 million hectares will be deforested until 2050. Another 156 million hectares pasture and other vegetated areas will be converted to cropland and built-up areas. In densely populated areas some cropland will also be converted to built-up land, which explains the discrepancy in cultivated land increases shown in Table 8 with those shown in Table 9.

Land use changes are faster in the first three decades compared to the period 2030 to 2050. For example annual deforestation rates amount to 2.3 million hectares between 2000 and 2030 and decrease to 1.4 million hectares in the period 2030 to 2050. For comparison the historical rate of deforestation in the 1990s and beginning of this century was estimated by FAO at 8-9 million hectares annually (FAO, 2005).

Land use changes are especially dynamic in Sub-Saharan Africa with 44% percent of global land use changes occurring in this region. Cultivated land and built-up area increase by 89 and 22 million hectares respectively. About two thirds of these 111 million hectares are converted from pastures and other vegetated areas and one third via deforestation.

Table 9. Changes in land use between 2000 and 2050, Reference Scenario

million hectares	Increasing land uses		Decreasing land uses	
	Cultivated	**Built-up**	**Forest**	**Pasture & other vegetated land**
WORLD	+ 174	+ 81	- 99	- 156
of which				
Developing countries	+170	+ 74	- 92	- 152
of which				
Latin America	+ 51	+ 8	- 27	- 32
Sub-Saharan Africa	+ 89	+ 22	- 34	- 77
South & Southeast Asia	+ 19	+ 24	- 23	- 20

Source: IIASA world food system simulations; scenario ELOBIO-REF.

3.2.7 Agricultural productivity

Development of agricultural productivity depends on available technology and management. The latter includes fertilizer use, cropping patterns and cropping intensity and is determined by farmers' socio-economic conditions.

In the WFS agricultural productivity is a function of fertilizer use and a technology factor with fertilizer use being endogenous and depending on demand and prices. The technology factor is exogenously determined by region and crop type with sources derived from FAO's projections and selected countries studies (esp. United States, China, India and Russia).

Describing agricultural productivity for regions or countries requires aggregation, which has been achieved in WFS by multiplication of individual crops with country specific world market prices (in $1970). Aggregate yields describe a country's crop production volume per unit of arable land. In the scenario *REF* aggregate yield are projected to double and to increase by 50% in respectively the developing world and the developed world between 1990 and 2050 (Table 10). Results for regions are shown in Figure 7.

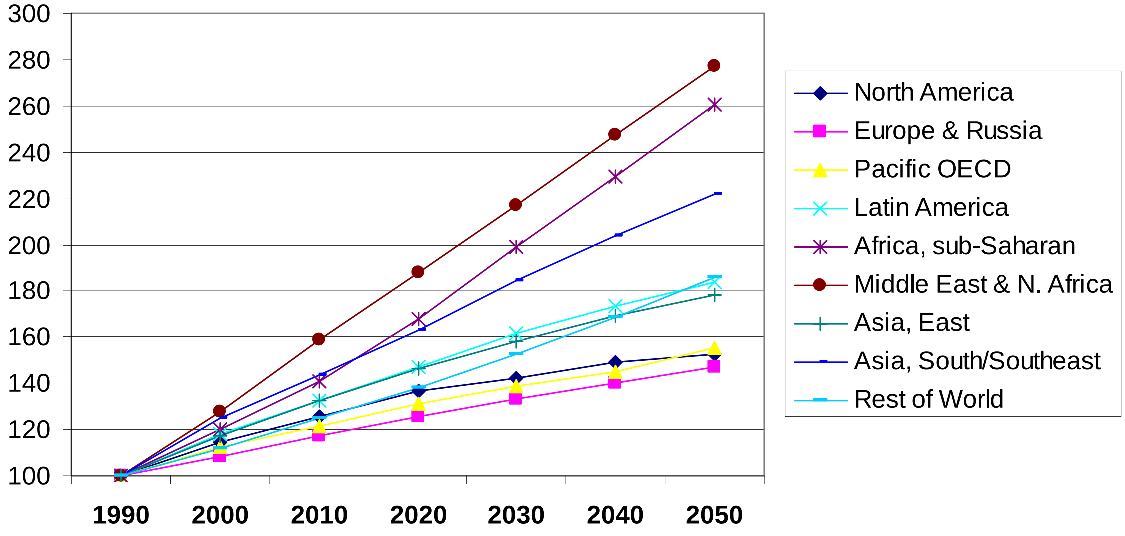
Table 10. Aggregate Crop Yields, Scenario *REF*

	Aggregate Yield Index (1990=100)						
	1990	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Developed	100	111	120	130	137	143	149
Developing	100	119	135	151	166	181	195
World	100	116	130	144	158	170	181

Source: IIASA world food system simulations; scenario ELOBIO-REF.

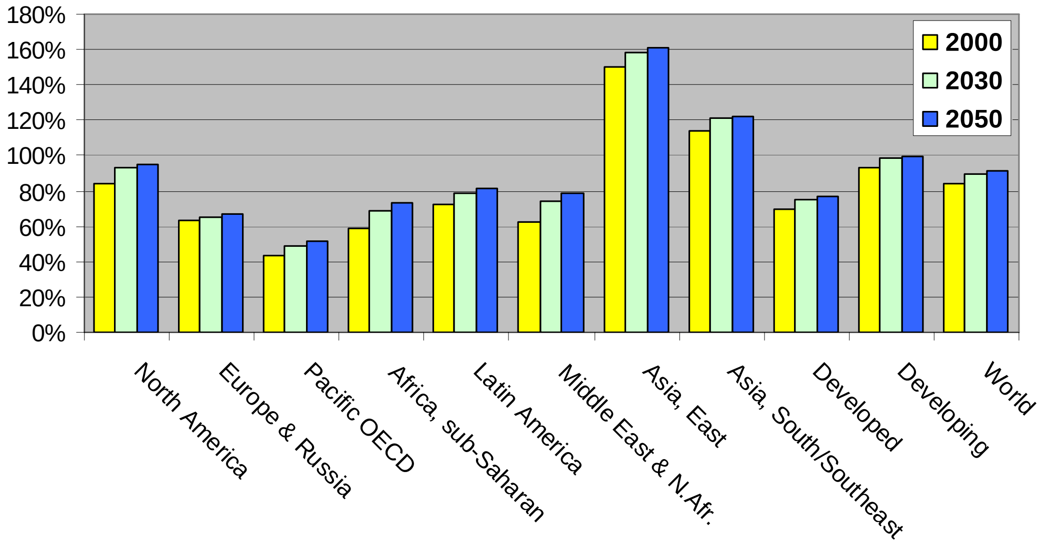
Increases in agricultural productivity are also reflected in increasing cropping intensity over time. Globally cropping intensity increases from 84 percent in 2000 to 92 percent in 2050 (Figure 8). Cropping intensity (the ratio of harvested area and arable land) differs widely across regions. In East, South and Southeast Asia the warm climate and intensive agricultural management enable to produce more than one harvest a year. In other regions fallow periods are required for sustainable production resulting in less than one harvests per ha of arable land (compare above Table 8 and associated text).

Figure 7. Aggregate Crop Yields, Index; Scenario *REF*



Source: IIASA world food system simulations; scenario ELOBIO-REF.

Figure 8. Cropping intensity in different regions in 2000, 2030 and 2050, Scenario REF



Source: IIASA world food system simulations; scenario ELOBIO-REF.

4 IMPACTS OF BIOFUEL EXPANSION

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

The potential savings of greenhouse gas emissions and climate change mitigation compared to fossil fuel use are a key requirement for biofuel deployment. The extent of GHG saving varies widely for individual biofuel production chains. Calculation of GHG saving potentials are further complicated by consideration of indirect land use changes, i.e. displayment effects such as agricultural expansion that is at least partly induced by a bio-energy feedstock production elsewhere. These issues have been in the centre of intense debates and controversy. The European Union has defined in its sustainability criteria a minimum requirement for GHG saving, relative to fossil fuels, of at least 35% from the outset, increasing by 2017 to 50% and 60% for new installations.

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.

4.1 Biofuel scenarios formulation

In general biofuel 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.).

In ELOBIO we've defined two biofuel scenarios used in the model simulations designed to cover a wide and plausible range of possible future demand for biofuels. While both scenarios assume transport energy demand as projected by IEA in its WEO 2008 Reference Scenario (*WEO2008-Ref*), they differ in their assumed level of biofuel use and show some variation in the share of second-generation biofuel production technologies.

The first scenario *WEO* assumes until 2030 regional biofuel use as projected by *WEO2008-Ref* and second-generation conversion technologies becoming commercially available after 2015 and being deployed gradually. Alternatively the scenario *TAR* assumes a fast expansion of biofuel production in accordance with mandatory, voluntary or indicative targets announced by major developed and developing countries. In *TAR* we assume an accelerated development of second-generation conversion technologies and permit rapid deployment.

4.1.1 Future projections of transport fuel use

For describing regional energy futures we used for both biofuel scenarios 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% per year on average in 2006-2030, from 11,730 Mtoe to just over 17,000 Mtoe (i.e. by about 45%). This projection embodies the effects of government policies and measures that were enacted or adopted up to mid-2008. The IEA World Energy Model - 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).

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 11. The level and regional pattern of total transport fuel consumption has been applied in both biofuels scenarios discussed in this paper.

Table 11. Final consumption of transport fuels by region

	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
Source: IEA, 2008a

4.1.2 Biofuel consumption

The biofuel scenario *WEO* assumes until 2030 regional biofuel use as projected by *WEO2008-Ref* scenario (IEA, 2008a). 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% 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 12). 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*).

Beyond 2030 assumptions on biofuel consumption become more speculative. Since ELOBIO aims at informing policy makers and markets, it was decided to include a longer term perspective until 2050 in the analysis. Between 2030 and 2050, both *WEO* and *TAR* assume biofuel consumption to increase according to a linear extrapolation of regional per capita biofuel consumptions between 2000 and 2030. Details of scenario assumptions are presented below.

Table 12. 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, 2009a

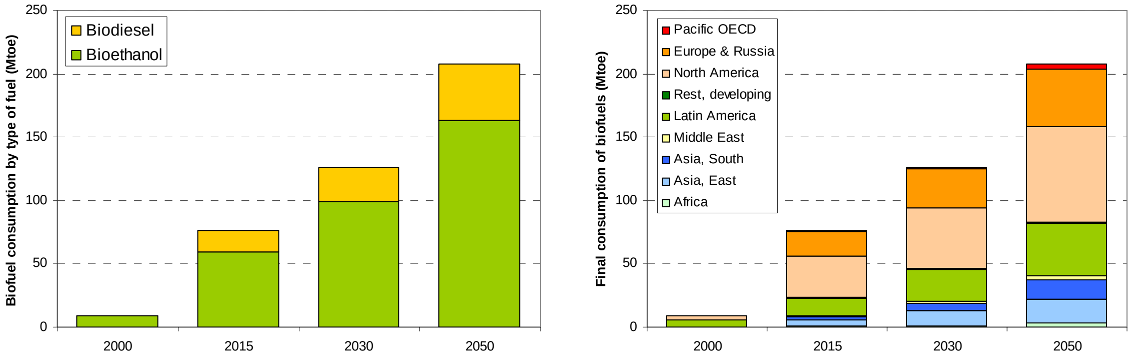
Figure 9 summarizes final consumption of biofuels in the *WEO* and *TAR* scenario; panel a) indicates the fuel split, panel b) shows a distribution by region.

Figure 9. Final consumption of biofuels in the WEO and TAR scenario

Final consumption of biofuels in the WEO scenario

a) Consumption by type of biofuel

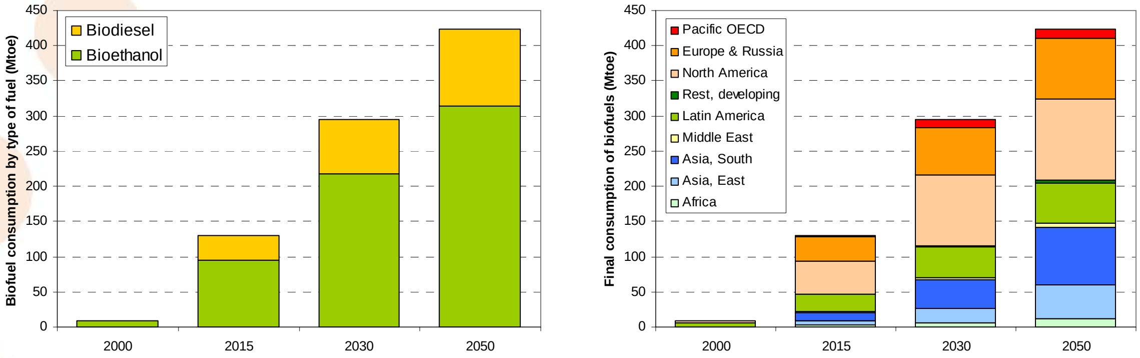
b) Consumption by region



Final consumption of biofuels in the TAR scenario

a) Consumption by type of biofuel

b) Consumption by region



Source: Fischer et.al, 2009a

The *WEO* scenario assumes final consumption of biofuels to reach some 120 million tons in 2030 and climbs to just over 200 million tons by 2050. Throughout the period about two thirds of biofuel is projected to be consumed in developed countries with the United States and EU-27 accounting for 90% of the developed countries use. However, the share of developing countries rises over time.

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% of biofuel use in developing countries, a combined share that decreases slightly to about 75% in 2050.

In the developed world, the projected share of biofuel consumption in total transport fuels use in 2020 amounts to 4.3% in the WEO scenario. By 2030 this share increases to 5.5%. For the developing world the WEO scenario projects a biofuels share in total transport fuel use in 2020 and 2030 at 2.7% and 3.0% respectively. At the global level this share comes to 3.5% in 2020 and 4.2% in 2030. It increases to 6% in 2050[18]. With a road transport share of 70%-75% of total transport fuel use, biofuels would account for respectively 4.5%, 5.4%, and 7.6% of road transport in 2020, 2030 and 2050[19].

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* projections.

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*.

Biofuel feedstocks

In both scenarios, *WEO* and *TAR*, current shares in feedstock use are maintained into the future (e.g. for the US it is assumed that 90% of biofuel feedstock demand is from corn).

4.1.3 Second-generation biofuels

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.

In the *WEO* and *TAR* scenario alternative views/expectations on the dynamics of technology deployment for second-generation fuels are represented. Specification was done by broad regions and follows simple and transparent assumptions. The assumptions used for ethanol are summarized in Table 13.

WEO 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 that second-generation conversion plants will take off as of 2020, occupying a share of 12.5 percent by 2030. The largest biofuel consumers in WEO 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.

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

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

The *TAR* scenario assumes an early and accelerated deployment of second-generation technologies. 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 *WEO* are 3 percent, 13 percent and 30 percent in 2020, 2030 and 2050 respectively and for scenario *TAR* the respective shares are 22, 38, and 55 percent.

Table 13. Share of second-generation biofuels in total biofuel consumption

Scenario	Region	Assumed share of second-generation ethanol in total bioethanol (%)			
		2015	2020	2030	2050
WEO	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
TAR	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, 2009a

4.1.4 First-generation biofuel feedstocks demanded in the biofuel scenarios

While in the reference scenario *REF* the amount of biofuels consumed in 2008 are kept constant for the entire remaining simulation period to 2050, the amounts increase in both the *WEO* and *TAR* scenario variants according to the assumptions described above. 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, vegetable oil, and sugar plants (included in the category 'Other food') required for transport biofuel production in 2020, 2030 and 2050 in the different scenarios is shown in Table 14.

Table 14. Use of agricultural commodities for biofuel production in different scenarios

Scenario	**Cereals** (million tons)			**Other food**[1] (million tons sugarcane equivalent)			**Vegetable oil** (million tons)		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
REF	83	83	83	387	387	387	10	10	10
WEO	181	206	246	915	1180	1678	26	30	44
TAR	238	272	262	1670	2318	2491	46	59	61

[1] In WFS sugar plants such as sugar cane or cassava are included in the category 'Other food'

Source: IIASA world food system simulations, ELOBIO scenarios.

4.1.5 Study scope and limitations

The scenario analysis presents a comprehensive evaluation of the social, economic and environmental implications of accelerated biofuels deployment. These results need to be considered in the context of the following scope and limitations of the study:

The WEO scenarios applies only one transport fuel scenario, namely the energy model derived reference scenario published in the World Energy Outlook 2008 by the International Energy Agency. The target scenario TAR has been constructed on the basis of announced biofuel targets before 2010. Historically targets and mandates have been by far the most important driver for increased biofuel demand. Political and socio-economic circumstances as well as technological developments have often been reasons for changing envisaged targets.

Today feedstocks for biofuel production are primarily derived from local production and the biofuel scenarios assume only small changes into the future. However biofuels may be traded more extensively in liberalized markets. For example, environmental impacts will change when more ethanol is produced from high yield crops such as sugar cane and imported into temperate zones (Europe and the United Stated).

The scenario analysis assesses the agronomic feasibility of biofuels targets but does not apply cost criteria to judge their economic viability, nor does it give specific consideration to possible other uses of biomass in the stationary sector (heat and electricity).

There are large uncertainties regarding the speed of second generation technologies development and deployment as well as costs and efficiencies. In the scenario analysis a plausible range for a possible contribution of second-generation feedstocks is considered via scenario variants, as proposed by current literature and expert opinion.

The assessments of net greenhouse gas emissions from biofuels presented in the study are subject to a considerable uncertainty range both with regards to life cycle results as well as land use change impacts. The range of individual biofuels feedstocks emissions information available in the literature has been used for both aspects.

4.2 Impacts on the food system

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 the two biofuel-expansion scenarios, *WEO* and *TAR*, to a reference projection (*REF*) of the world food system simulated without imposing additional biofuel demand. Results of the reference projection were presented in section 3. In *WEO* and *TAR* all other 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 labour migration between sectors as well as reallocation of resources within agriculture. Time is an important aspect in this adjustment process.

4.2.1 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 15). The exception is protein feed where increased biofuel consumption in *WEO* and *TAR* implies lower prices compared to *REF* caused by biofuel by-products entering the market in large volumes (livestock feed from starch based ethanol production and protein meals and cakes from crushing of oilseeds). Having access to cheaper feed sources also results in only modest increases of livestock product prices.

Table 15. Impacts of biofuel expansion scenarios on agricultural prices

	Change of price index relative to reference scenario REF (percentage)							
Scenario	***WEO***				***TAR***			
	2020	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Crops	10	8	9	10	21	16	14	13
Cereals	10	8	8	10	19	14	12	11
Other crops	10	7	9	10	22	17	15	14
Livestock	3	0	0	0	4	0	-1	-1
Agr. Production	8	5	6	7	16	11	10	9
Agr. Exports	7	4	5	6	13	9	8	7
Wheat	14	8	12	14	20	15	14	16
Rice	5	3	5	7	9	6	7	10
Coarse grains	11	11	7	8	23	18	13	7
Bovine & Ovine	3	0	-1	0	5	0	-2	-2
Dairy	3	1	1	1	7	2	0	0
Other meat	2	-1	-1	-1	3	-1	-2	-2
Protein feed	-21	-28	-28	-29	-30	-40	-34	-32
Other food	13	10	11	12	26	21	18	17
Non-food	-2	0	2	4	0	-3	-4	0

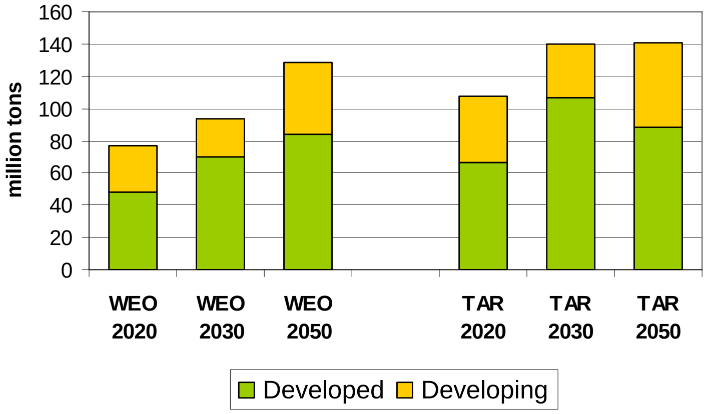
Source: IIASA world food system simulations, ELOBIO scenarios.

For 2020, the price increases for both cereals and other crops under the *WEO* scenario are in the order of 10 percent. For biofuel demand specified in the *TAR* scenario (i.e. about twice the level projected in the *WEO* scenario) the price impact on crops including cereals would be about 19 percent. With accelerated deployment of second-generation fuels the price impact of the *TAR* scenario decreases and even the large volumes of biofuels produced in *TAR* can be achieved with price increases of only about 15 percent, only slightly higher than those of *WEO*.

4.2.2 Cereal demand and production

In scenario *REF* total production of cereals increased from 2.1 billion tons in 2000 to nearly 3 billion tons in 2030 and 3.5 billion tons in 2050. 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 labour. At the same time, consumers react to price increases and adjust their patterns of consumption. Figure 10 shows the producer response of cereal sectors for the different biofuel scenarios in 2020, 2030 and 2050, i.e. the amount of additional cereal production realized in each scenario compared to REF.

Figure 10. Change in cereal production of biofuel scenario's WEO and TAR, relative to REF



Source: IIASA world food system simulations, ELOBIO scenarios.

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 *REF* is around 80 million tons in *WEO* and 115 million tons in *TAR*. The additional demand increases to 130 to 140 million tons by 2050 (Figure 10), an increase of about 4% compared to *REF*.

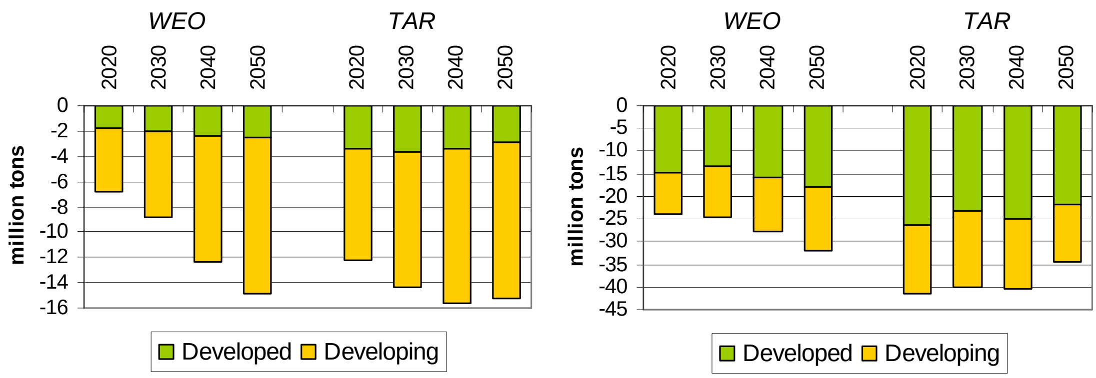
Production increases in response to higher agricultural prices are stronger in developed countries, as are the reductions in feed use (Figure 10 and 11b). When it comes to food use, however, consumption in developed countries is less responsive than in developing countries, which account for 75 percent of the 'forced' reduction in cereal food consumption (Figure 11a).

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. 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, of which reduced feed use accounts for a quarter of the amount of cereals used for biofuel production. The remaining 10% is related to reduced food use, primarily in the developing world with negative impacts on risk of hunger.

Figure 11. Change of cereal use for biofuel scenarios, relative to baseline *REF*

a) Change in direct food use

b) Change in feed use



Source: IIASA world food system simulations, ELOBIO scenarios.

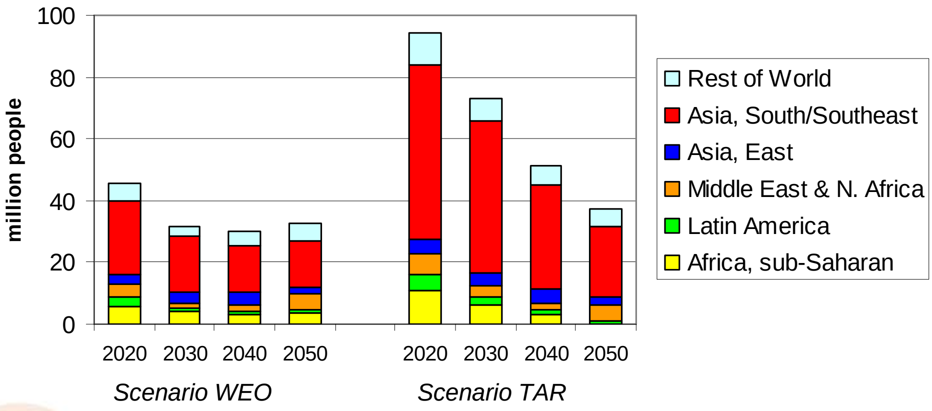
4.2.3 Risk of hunger

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. In the baseline scenario *REF* the number of people at risk of hunger peak in 2010 with 951 million people. By 2050 a 44% decrease is estimated with 531 million people still remaining at risk of hunger (see Figure 5).

The additional production of first-generation biofuels causes higher prices and results in additional number of people at risk of hunger compared to the reference projection. Figure 12 presents the simulated regional distribution of additional undernourished in different biofuel scenarios, showing a large impact in particular in South Asia. 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.

Higher prices reduce food consumption in developing countries and result by 2020 in 44 million additional people at risk of hunger in *WEO*. Despite of ambitious assumptions on introduction of second-generation technologies in the near future, the higher biofuel consumption in the TAR scenario increases the number of people at risk of hunger by as much as 94 million (compared to *REF*) by 2020. The swift introduction of second generation technology in scenario TAR takes pressure off the competing food-feed-biofuel feedstock market and reduces the additional number of people at risk of hunger over time. Nevertheless by 2050 the number of people at risk of hunger is still about 6% higher in the biofuel scenarios compared to the reference scenario with no increased biofuel consumption.

Figure 12. Additional people at risk of hunger relative to baseline REF



Source: IIASA world food system simulations, ELOBIO scenarios.

4.2.4 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 *REF*, with no additional biofuels after 2008, is shown in Table 16.

Table 16. Impacts of biofuel expansion scenarios on agricultural value added

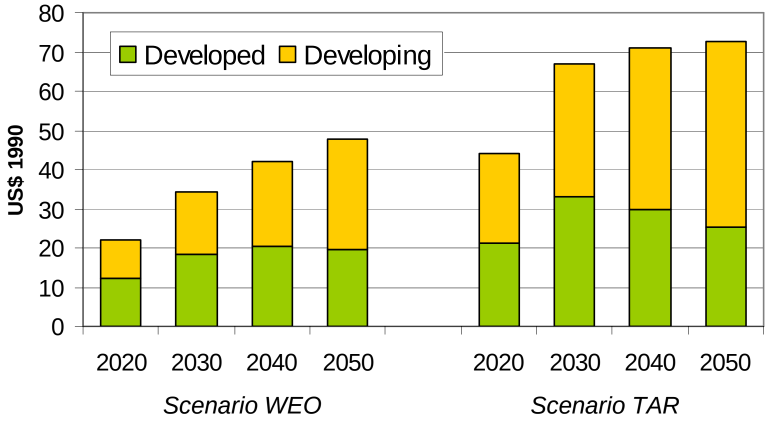
	Change in Agricultural Value Added relative to reference scenario REF (percentage)							
	Scenario WEO				**Scenario TAR**			
	2020	2030	2040	2050	2020	2030	2040	2050
Developed	2.4	3.5	3.7	3.4	4.3	6.4	5.4	4.4
Developing	0.9	1.3	1.6	1.8	2.1	2.7	3.0	3.1
World	1.4	1.9	2.1	2.2	2.8	3.7	3.6	3.4

Source: IIASA world food system simulations, ELOBIO scenarios.

As indeed expected, agricultural value added increases for all biofuels scenarios at the global and regional levels. Increase rates for the world are between 1.5 and 3.7% depending on biofuel scenario and time. There is a strong regional disparity with the developed world increasing their value added more than the developing countries throughout the projection period. Thus the agricultural sectors in developed countries benefit relatively more than in developing countries in terms of percentage gains relative to the baseline. The highest gains are projected for North America peaking in the 1930s with over 6% relative to baseline.

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 2020 to 2030, and on average 40 percent of the projected gains in 2050. Figure 13 highlights the gain of the biofuel scenarios in absolute terms.

Figure 13. Gain in agricultural value added for biofuel scenarios in relation to reference scenario *REF*, 2020 to 2050



Source: IIASA world food system simulations, ELOBIO scenarios.

4.3 Impacts on the environment

4.3.1 Arable land expansion

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, fibre products) on arable land currently in production.

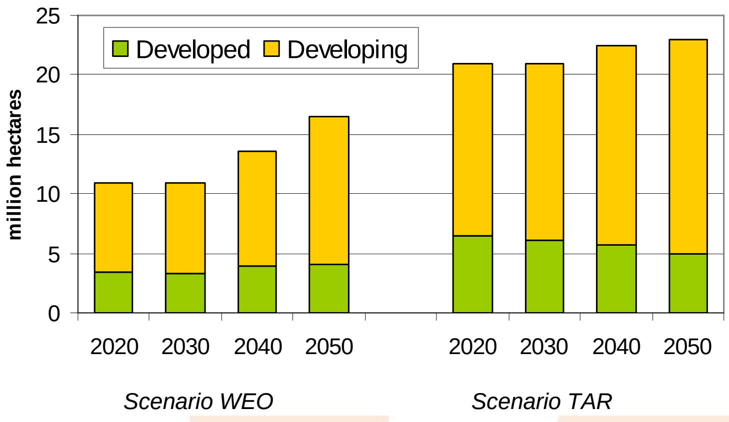
The approach pursued in this study is to apply a general equilibrium framework that can capture both direct and indirect land use changes by modelling responses of consumers and producers to price changes induced by introducing competition with biofuel feedstock production. This approach accounts for 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 the baseline projection REF, the expansion of arable land to meet growing future food and feed requirements amounts to about 120 and 170 million hectares by 2030 and 2050 respectively (see Table 8). The impact of biofuel scenarios on arable land use is shown in Figure 14. For the biofuel scenario *WEO* an additional 11 million hectares is put into cultivation compared to the reference projections by 2020 increasing to 17 million hectares by 2050. This represents a 10% net arable land expansion due to biofuel use in *WEO*.

The biofuel scenario TAR with about twice the amount of biofuels consumed compared to WEO results in a conversion of 22 million hectares into arable land use representing a net arable land expansion of 18%. Due to accelerated deployment of second-generation biofuel technologies in TAR after 2020 little additional land is put into cultivation compared to the REF.

In both biofuel scenarios more than two thirds of the additional arable land expansion occurs in Africa and Latin America.

Figure 14. Additional arable land use in biofuel scenarios relative to reference scenario



Source: IIASA world food system simulations, ELOBIO scenarios.

4.3.2 Deforestation

A large and rapid increase in inelastic biofuel demand can lead to cropland extension into natural ecosystems via direct or indirect land use changes. Land conversion is explicitly modelled to maintain full consistency between the spatial agro-ecological zones approach used for appraising land resources and land productivity and the expansion of cultivated land as determined in the world food system model. The modelling framework projects spatially explicit agricultural land use expansions. For the base year 2000 satellite derived land cover interpretations have been used together with statistical data from the FAO to derive a consistent spatial characterization of each land grid-cell (at 5 by 5 minute longitude/latitude). The impact of biofuels production on land use has been quantified by comparing land use development for each biofuel scenario with the land use resulting in the reference scenario without accelerated biofuel use.

Table 17 provides an estimation of the amount of additional deforestation directly and indirectly caused by biofuels feedstock production.

Table 17. Additional deforestation (relative to REF) of biofuel scenarios by 2030 and 2050

million hectares	until 2030		until 2050	
Scenario	WEO	TAR	WEO	TAR
WORLD	4.5	8.9	6.6	9.6
Developed	1.4	2.8	1.6	2.0
Developing	3.1	6.1	4.9	7.5
of which				
Latin America	1.8	3.4	3.0	4.8
…Africa, Sub-Saharan	0.8	1.6	1.1	1.4
Asia, South / Southeast	0.3	0.7	0.5	0.8

Source: IIASA world food system simulations, ELOBIO scenarios.

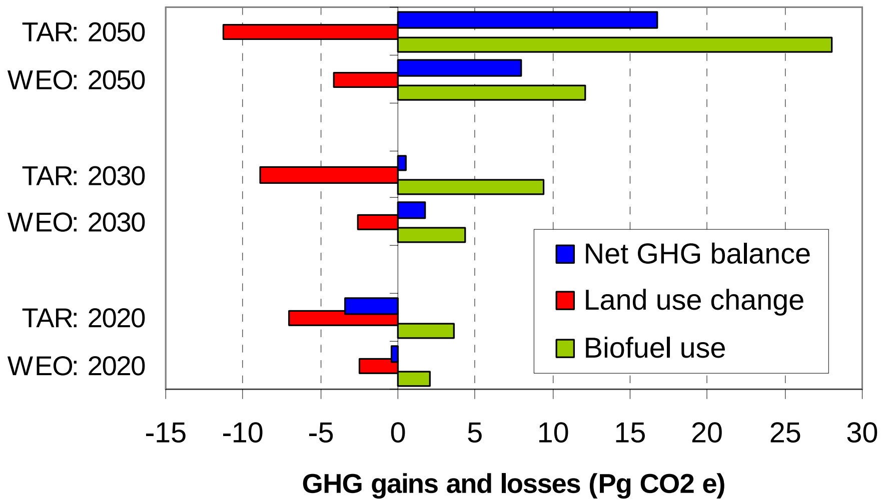
Results indicate that by 2030 biofuel feedstock production may be responsible for up to 9 million hectares of additional deforestation, i.e. a 10% increase compared to a world without biofuel expansion. Estimates indicate the vast majority of additional deforestation occurring in Latin America. Due to second-generation biofuels, the additional deforestation rates significantly slow down after 2030. It should be noted that in the biofuel scenarios potential production of ligno-cellulosic feedstocks for the second-generation production chains is assumed to occur on pastures and other wooded areas and will thus cause no additional deforestation.

4.3.3 Greenhouse gas emission saving

Since climate benefits and greenhouse gas (GHG) emission savings are a prime goal of biofuel consumption, a net reduction of GHGs of the whole lifecycle of biofuel production and consumption including land use change effects is imperative for accelerated biofuel deployment. This is reflected in the sustainability criteria currently established for biofuel consumption. There is an intense debate about the importance of land use changes when previously unused or differently used land is converted to production of biofuel feedstocks. Conversion and changed land management practices to produce biofuel feedstocks (direct land use change) and displacing agricultural activities to other areas and causing land use change somewhere else (indirect land use changes) due to regional development induced by biofuel initiatives can lead to both carbon losses or gains in the biospheric carbon stock. Of particular concern for greenhouse gas impacts is conversion of carbon-rich habitats such as forests, natural grassland, or wetlands to cultivated land.

Figure 15 highlights the cumulated net GHG savings of the biofuel scenarios WEO and TAR. The net GHG balance of a biofuel scenario is determined by the GHG savings achieved from biofuel replacement of gasoline and diesel (Bar “Biofuel use”) minus the GHG emissions caused by direct and indirect land use changes (Bar “Land use change”).

Figure 15. Cumulative net GHG savings of biofuel scenarios



Source: IIASA world food system simulations, ELOBIO scenarios.

Carbon losses from vegetation and soils due land use changes (deforestation and grassland conversion) occur mainly at the time of land conversion. By 2050, additional grassland conversion due to biofuel consumption amounts to 11 and 15 million hectares for WEO and TAR respectively. In addition 6.6 and 9.6 million hectares can be attributed to additional deforestation (Table 17).

In contrast GHG savings resulting from the replacement of fossil fuels with biofuels accumulate only gradually over time. For the biofuel scenarios WEO and TAR net GHG balances only become positive after 2020. By 2050 the amount of second-generation biofuels increases GHG savings via biofuels use while at the same time only little additional land use conversion is required. This results in a maximum accumulated net GHG savings of 22 Pg CO2 equivalent (TAR scenario). It should be noted that by 2050 it is assumed that 50% of biofuel consumptions is achieved from the second-generation conversion pathways.

For comparison, in 2004, the road transport sector produced 4.7 Pg CO_2 emissions globally (IPCC Fourth assessment report, Climate Change 2007: Mitigation of Climate Change).

4.3.4 Fertilizer use

While additional fertilizer use is required to increase agricultural productivity in certain regions of the world, intensive use of fertilizers generally results in higher greenhouse gas emissions and depending on management practices may cause soil and water pollution.

The impact on fertilizer use of accelerated use of biofuels assumed in the scenarios WEO and TAR is relatively small compared to a reference scenario without additional biofuel consumption (Table 18). In the reference scenario REF fertilizer use is expected to increase by 63% with four fifths of the increase occurring in the developing world. Additional fertilizer use due to increased biofuel consumption is less than 5% compared to fertilizer use in REF.

Table 18. Nitrogenous fertilizer use 2000 - 2050

million tons		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	Increase 2000-2050
Reference scenario		Nitrogenous fertilizer use						
REF	World	83	97	109	119	128	135	63%
	of which							
	developed	27	29	31	32	33	34	26%
	developing	54	64	74	83	91	97	82%
Biofuel scenarios		Additional nitrogenous fertilizer use, compared to REF						
WEO	World	0.0	0.3	1.9	2.8	3.1	3.6	
TAR	World	0.0	1.0	2.8	5.1	4.5	4.4	

Source: IIASA world food system simulations, ELOBIO scenarios.

4.3.5 Land required for second generation biofuels

As demonstrated above 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.

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. Substantial government grants have recently been made available to develop so called second-generation feedstocks and conversion technologies including biofuels produced from woody or herbaceous non-food plant materials.

The energy yields per hectare achievable with second-generation feedstocks are generally higher than those of first-generation biofuels (except for sugarcane ethanol). In addition 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.

A recent IEA report 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 19.

Table 19. 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 for the biofuels scenarios of this study in a biomass demand for second-generation biofuels as listed in Table 20.

Table 20. 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	19	106	370	19	95	300
TAR	315	725	1402	297	583	875

Source: Fischer et.al, 2009a.

Rapid deployment of second-generation conversion technologies after 2015 in order to meet the biofuel production of the target (*TAR*) 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.

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 21.

Table 21. Typical yields of second-generation biofuel feedstocks[20]

	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 20 implies that by 2020 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, then an upper limit of land required for feedstock production would be 50 million hectares in the *TAR* scenario and less than 20 million hectares in the *WEO* scenario.

5 SENSITIVITY ASSESSMENT OF KEY VARIABLES

The ELOBIO project team in collaboration with stakeholders (including two workshops and one questionnaire) has identified the following key issues of particular relevance for studying impacts of increased biofuel consumption on food markets and the environment. They include growth in agricultural productivity, the importance of biofuel by-products, and land use restrictions. The following discusses these issues by assessing variants of the biofuel scenarios.

5.1 The importance of biofuel by-products

First-generation biofuels production chains generate significant quantities of by-products that can be used as valuable animal feed. Depending on quantities they can for example substitute for imported animal feed and potentially reduce input costs for the farmer and increase European self-sufficiency in agricultural commodities. They may as well exceed the absorption capacity of markets and affect other industries. The role of by-products is a crucial element in the debate on pros and cons of increased first generation biofuel deployment.

The animal feed industry has productively utilized the by-products associated with the refining of oilseeds into higher value food material and more recently into biodiesel. In the case of soybean, the soymeal by-product is usually the prime reason for soybean production.

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

While grain ethanol fermentation consumes the grain's starch, the protein, minerals, vitamins, fat and fibre can be concentrated during the production process to produce highly valued and nutritious livestock feed. In its wet form these by-prducts are known as wet distillers grains with solubles (WDGS) and can be sold to nearby markets. The dried form, dried distillers grains with solubles (DDGS), can be transported over long distances and is available for domestic markets and for exports. For every ton of ethanol produced from starchy crops, a ton of DDGS is produced. In the ELOBIO modelling it is assumed that all DDGS produced will enter commodity markets and will be used as animal feed.

To investigate the importance of biofuel by-products, sensitivity scenario runs of the biofuel scenarios highlight the importance of the use of DDGS as animal feed. In the scenario variants *WEO-DDGS* and *TAR-DDGS*, DDGS do not enter the animal feed market while all other assumptions remain unchanged[21].

It should be noted that the possibility of not using DDGS is considered to be unlikely since ethanol biorefineries are designed to produce WDGS or DDGS. However animal feed compositions may have to be redesigned when DDGS replaces conventional livestock feed. Some agricultural extension services may be required to ensure a smooth swift towards using DDGS.

The main impact of not using DDGS as animal feed will be an increased requirement for feed crops for livestock production with effects on agricultural prices (especially for the animal feed and livestock sector) and increased arable land requirement for growing the feed crops, which replace DDGS.

Price effects

The impact of the biofuel scenarios WEO and TAR on agricultural prices has been discussed in Section 4.2.1. Table 22 shows agricultural prices in 2030 and 2050 in relation to the reference scenario for the biofuel scenario with two variants regarding use of DDGS.

Table 22. Agricultural Prices for biofuel scenarios and variants in 2030 and 2050, in relation to reference scenario

	2030				2050			
Scenario	WEO		TAR		WEO		TAR	
Variant: **DDGS use**	yes	no	yes	no	yes	no	yes	no
Crops	8	12	16	23	10	15	13	17
Livestock	0	2	0	4	0	2	-1	1
Agric. Production	5	9	11	18	7	11	9	13
Wheat	8	15	15	24	14	19	16	22
Rice	3	6	6	11	7	12	10	13
Coarse grains	11	18	18	31	8	18	7	15
Bov & Ovine	0	1	0	3	0	1	-2	-2
Dairy	1	3	2	6	1	3	0	2
Other meat	-1	2	-1	4	-1	3	-2	3
Protein feed	-28	7	-40	8	-29	12	-32	9
Other food	10	11	21	24	12	14	17	18

Source: IIASA world food system simulations, ELOBIO scenarios.

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[21] Not using protein meals and cakes from crushing of oilseeds for biodiesel production was not considered as a scenario variant since protein feed and vegetable oil are tighly linked joint products of oilseed plant production.

In both scenarios WEO and TAR commodity price increases are generally higher when DDGS is not used as animal feed. As expected the strongest effect can be seen for protein feed, where price decreases caused by increased biofuel consumption turn into price increases, when DDGS is not being used as animal feed. In the crops sector model results show a substantial price dampening effect of using DDGS. By 2030 crop prices would increase by 12 and 23 percent in WEO and TAR compared to reference, while the use of DDGS reduces these price increases to 8 and 6 percent.

Increased agricultural prices result in additional number of people with risk of hunger. Model results show the largest number of additional numbers because DDGS in not being used in Scenario *TAR* in 2030 amounting to 29 million people.

Land use effects

As described above the biofuel scenarios result in additional arable land requirements by 2020 of 10 and 21 million hectares for respectively the WEO and TAR scenario. By 2050 these figures increase to 16 and 24 million hectares (Figure 13). These figures assume that all DDGS generated during grain-based ethanol production is used for animal feed.

Table 23 highlights how much *additional* arable land would be required provided that DDGS were not used as animal feed. An effect of around 1.5 million hectares is visible even in the reference scenario *REF*, which assumes no increases in biofuels but continued biofuels consumption at the level of 2008. For the biofuel scenario WEO additional arable land requirements are 5.6 million hectares in 2030 and 6.6 million hectares in 2050. For scenario TAR additional arable land is 7.8 million hectares in 2030. By 2050, when second-generation technologies gain in importance in TAR, additional arable land requirements are 7.1 million hectares compared to a scenario when all DDGS is used as animal feed.

Table 23. Additional arable land required because DDGS is not used as animal feed, 2030 and 2050 for scenarios REF, WEO and TAR

million hectares	2030			2050		
Scenario	**REF**	**WEO**	**TAR**	**REF**	**WEO**	**TAR**
Developed	0.6	2.2	2.8	0.0	1.6	1.8
Developing	0.8	3.2	4.7	1.3	4.9	5.1
World*	1.5	**5.6**	**7.8**	1.4	**6.6**	**7.1**

* includes Rest of World

Source: IIASA world food system simulations, ELOBIO scenarios.

In summary the 'land saving' effect of using DDGS as animal feed amounts to between 5 and 8 million hectares for the biofuel scenarios with around two thirds of the effect in the developing world. If DDGS were not used as animal feed the GHG balance of biofuel consumption would worsen significantly due to additional land use conversions and associated carbon losses.

5.2 Agricultural productivity growth

Growing markets for food, feed and bio-energy on the demand side together with land and water scarcity, climate change and rising input prices on the supply side will cause tighter global grain markets in the future. Environmental concerns including climate change, biodiversity loss and land degradation pose additional constraints on agricultural management, expansion of cultivated areas and production potentials. With declining availability of water and land that can be profitably brought under cultivation, expansion in area will contribute little to future production growth (Rosegrant et.al, 2009). Since area expansion of prime cultivated land can at best be small, future agricultural growth will be more reliant on raising crop and animal yields than in the past four decades. Much of the concern about feeding the world in 2050 relates to the slowing of yield growth in major cereals over the past three decades (World Bank, 2007).

A multitude of factors can increase yields ranging from technology, typically higher yielding varieties, and management, such as increasing input use and reducing losses from pest and diseases, to broader policy and institutional factors including information and skills of farmers, risk management, and irrigation infrastructure development.

A region's farm yield denotes the average yield achieved by farmers in a defined region over several seasons. Yield gaps describe the difference between farm yields and potential yields, with the latter being the maximum achievable yield with latest varieties and removing all constraints, especially constraints related to moisture and pest and diseases. Sub-Saharan Africa has been and still is a region with persistently high yield gaps.

Over the past five decades, global cereal yields have grown linearly at a constant rate of 43 kg/ha annually and with very low variability around the trend. However the close linear trend in yield growth at the global level hides considerable heterogeneity in performance by crop and region. Maize has been most dynamic, showing a linear trend at the global level, and an accelerating trend in the developing world. Both South Asia and Latin America show accelerating trends in absolute terms, while only Western Europe shows a declining trend. In contrast there is evidence of a slowdown in absolute yield growth for rice and wheat (Fischer et.al, 2009c).

Development of agricultural productivity in the WFS modelling employed in this study depends on an exogenous technology factor and endogenously modelled fertilizer use as a function of demand and prices. Aggregated levels of crop yields in the reference scenario have been described in section 3.2.6. Here the aim is to explore the impact of higher (than in reference) productivity growth.

Scenario assumptions

A scenario variant for the two biofuel scenarios WEO and TAR, termed WEO-vP and TAR-vP was defined to assess the impact of increased agricultural productivity. For this purpose we've defined three groups of countries based on available yield gap estimates and assumed productivity growth in the reference scenario *REF*. Yield gaps were estimated by comparing aggregated agricultural production of the year 2000 with rainfed yields potentials derived from the Agro-Ecological Zones calculations.

By comparing potential productivity growth with n addition yield gaps were compared with potential productivity growth assumed in the reference scenario *REF*. Thus unreasonable high productivity growth could be excluded.

The country grouping and technical factor of the agricultural productivity growth is modified in relation to REF as shown in Table 24. Yields start becoming higher compared to *REF* as of

2010. Agricultural productivity growth is for country group 1 including Sub-Saharan Africa assumed to be 7.5% higher by 2025 and 20% higher by 2050. The respective increase rates for country group 2, which includes India and most countries of Central and South America are +4% by 2025 and +10% by 2050. It should be noted that for all countries the resulting agricultural productivity is still well below the regions biophysical potentials.

Table 24. Assumptions on productivity growth for Scenarios *WEO-vP* and *TAR-vP*

	Increases in technical factor of crop yield productivity growth relative to REF		
Country group	**2010**	**2025**	**2050**
Group 1: high productivity growth Sub-Saharan Africa	starting	+ 7.5 %	+ 20 %
Group 2: medium productivity growth India, Pakistan, Indonesia, Thailand, Mexico, Argentina, Central & South America, North Africa, Far East Low Income, Middle East Low Income;	starting	+ 4 %	+ 10 %
Group 3: no productivity growth all countries not mentioned in Group 1 and 2 (includes all developed countries and China and Brazil)		no increases	

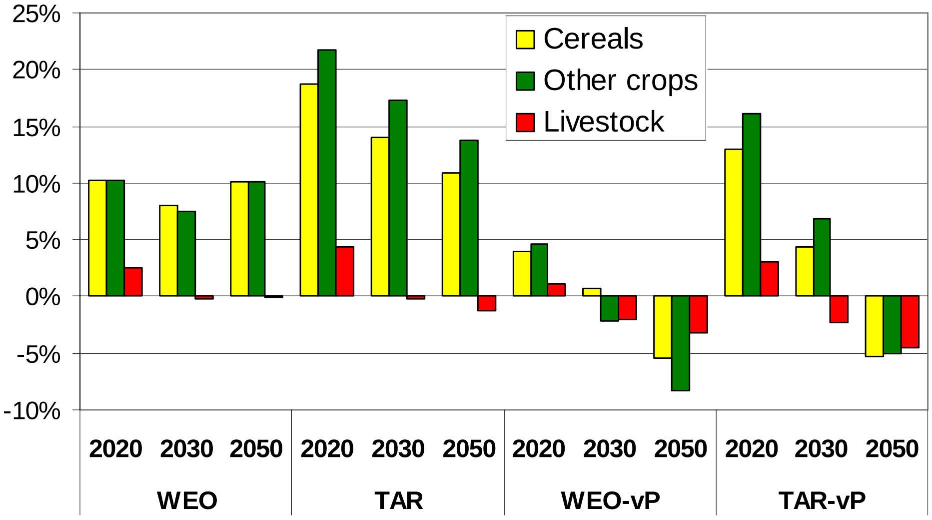
Scenario results

The following summarizes scenario results for WEO-vP and TAR-vP and compares with the biofuels scenarios without additional agricultural productivity growth (WEO and TAR).

Price development

The assumed additional productivity growth rates have a strong impact on the price development of agricultural commodities especially after 2030. Figure 16 compares price developments in the biofuel scenarios with and without additional agricultural productivity growth.

Figure 16. Agricultural prices for biofuel scenarios, relative to *REF*



Source: IIASA world food system simulations, ELOBIO scenarios.

While the biofuel scenarios WEO and TAR show significant prices increase compared to REF (see Table 15), in WEO-vP and TAR-vP prices increases are generally lower for all commodities (see Table 25 for price developments in WEO-vP and TAR-vP for different agricultural commodities). While in the near term (until 2020) price increases relative to REF are also observed for WEO-vP and TAR-vP, yet at lower levels than the scenarios WEO and TAR with lower levels of agricultural productivity growth.

After 2030 the impact of the productivity growth is apparently stronger than the additional demand for first generation biofuel feedstocks and prices become even lower compared to a situation where neither additional biofuel consumption nor additional productivity growth as assumed in the reference scenario REF.

Table 25. Impacts of biofuel expansion scenarios on agricultural prices

	Change of price index relative to reference scenario REF (percentage)							
Scenario	*WEO-vP*				*TAR-vP*			
	2020	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Crops	4	3	-4	-8	15	10	2	-6
Cereals	4	4	-3	-7	13	7	1	-6
Other crops	5	2	-4	-9	16	12	2	-6
Livestock	1	0	-3	-4	3	0	-4	-5
Agr. Production	3	2	-3	-7	11	7	0	-6
Agr. Exports	2	0	-5	-8	9	5	-1	-7
Wheat	9	7	0	-4	16	11	6	-1
Rice	-3	-5	-12	-17	1	-3	-9	-16
Coarse grains	4	6	1	-4	18	12	4	-4
Bovine & Ovine	1	1	-3	-4	4	1	-4	-6
Dairy	2	1	-3	-4	5	2	-4	-6
Other meat	1	-1	-3	-4	2	-2	-4	-5
Protein feed	-24	-32	-31	-33	-31	-44	-38	-36
Other food	7	5	-2	-7	20	16	5	-4

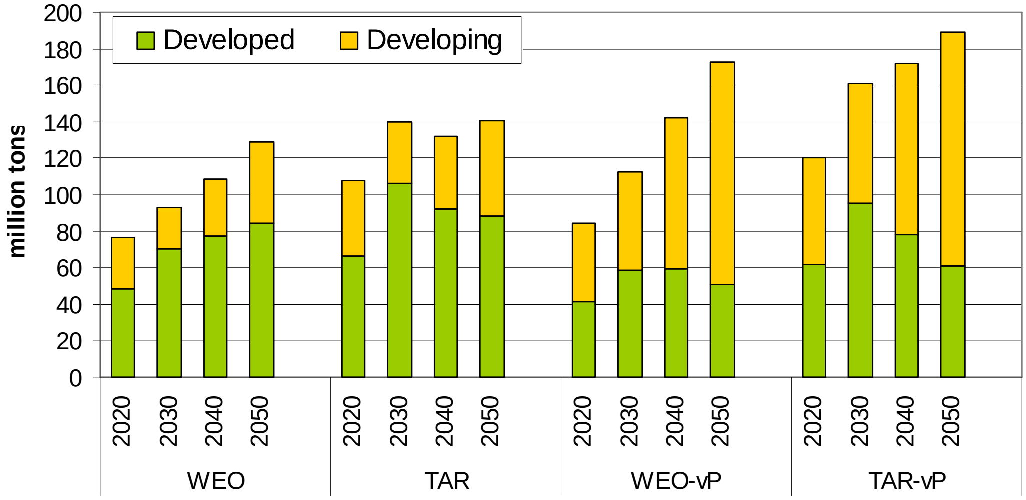
Source: IIASA world food system simulations, ELOBIO scenarios.

Agricultural markets

The assumed productivity growth in the developing world increases the region's competitive position and stimulates higher production. Compared to REF the developed countries loose market shares and cereal production increases over time in the developing world. Figure 17 shows development of cereal production in the different biofuel scenarios.

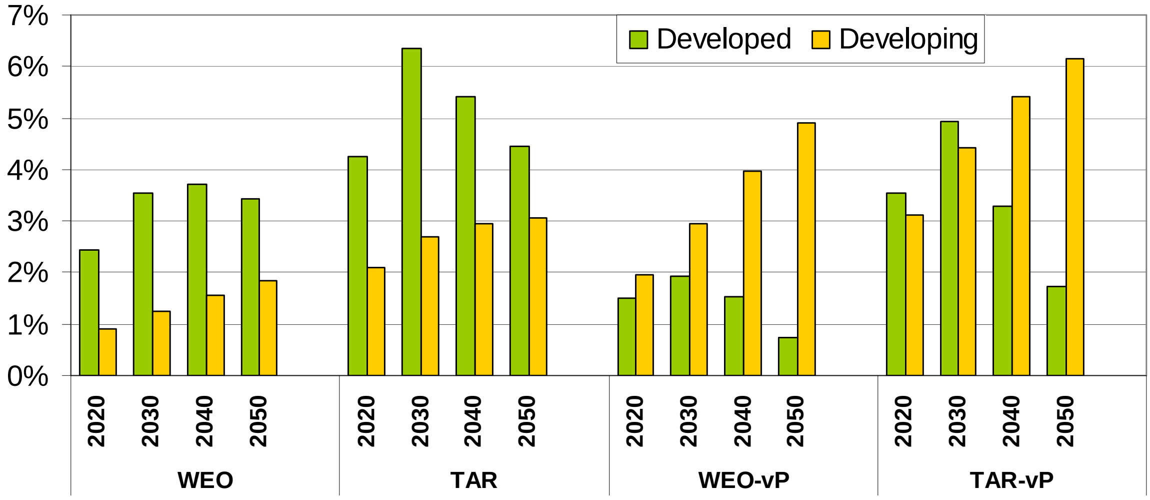
As a result the value added from the crop and livestock sector increases compared to REF and the share of developing countries in total value added increases. Figure 18 highlights the gains in value added (additional value added) from the crop and livestock sector between 2020 and 2050 for the two biofuel scenarios (WEO and TAR) and their variants with additional growth in agricultural productivity (WEO-vP and TAR-vP).

Figure 17. Additional cereal production for biofuel scenarios, relative to *REF*



Source: IIASA world food system simulations, ELOBIO scenarios.

Figure 18. Gain in value added from crop and livestock sector due to biofuel consumption, relative to *REF*



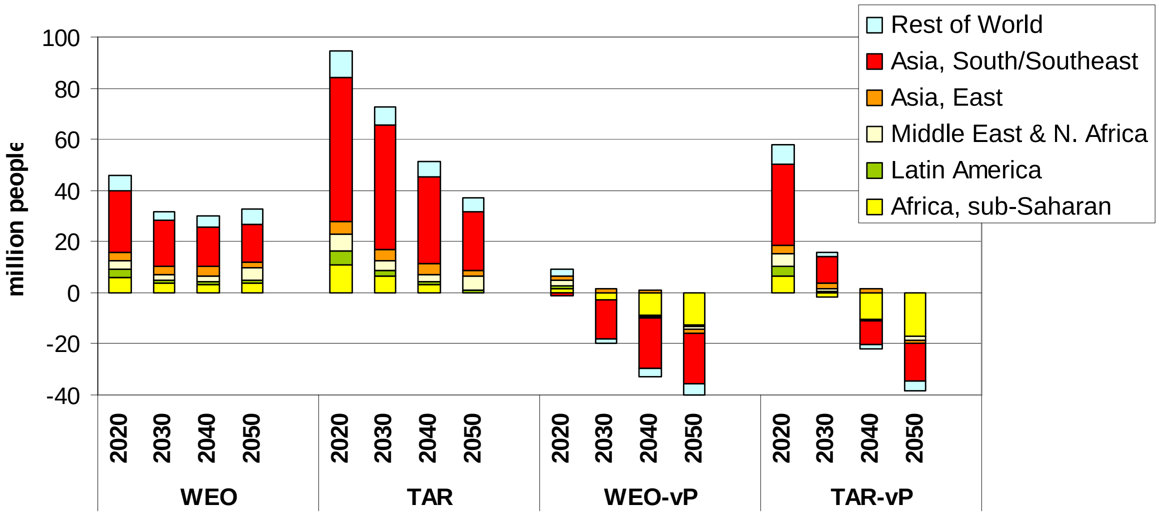
Source: IIASA world food system simulations, ELOBIO scenarios.

Hunger

Lower prices, more agricultural production and increased value added in agriculture in developing countries have a positive effect on the number of hungry people. The strong effect of productivity growth on hunger is visible in a variation of the reference scenario *REF-vP*, which assumes no accelerated biofuel production but additional productivity growth. The number of people of risk of hunger decreases by 80 million reaching 451 million compared to 531 million in *REF* in 2050. Thus an estimated 80 million people could elude their risk of hunger due to the assumed productivity growth in the scenarios.

In the biofuel scenarios WEO-vP and TAR-vP the number of people at risk of hunger decreases faster compared to the scenarios WEO and TAR without additional agricultural productivity growth. While between 2000 and 2050 the number of people at risk of hunger decreases by about 36% in WEO and TAR, the decrease in WEO-vP and TAR-vP is 46% reaching 480 million in both scenarios by 2050. After 2030 the productivity growth assumptions in WEO-vP and TAR-vP are strong enough to outweigh the additional number of people at risk of hunger due to biofuel demand. As a result there are less hungry people in the biofuel scenarios WEO-vP and TAR-vP compared to REF with no additional biofuel demand (Figure 19). Nonetheless the number of people at risk of hunger remains even in 2050 at 400 million.

Figure 19. Additional people at risk of hunger in different biofuel scenarios, relative to REF

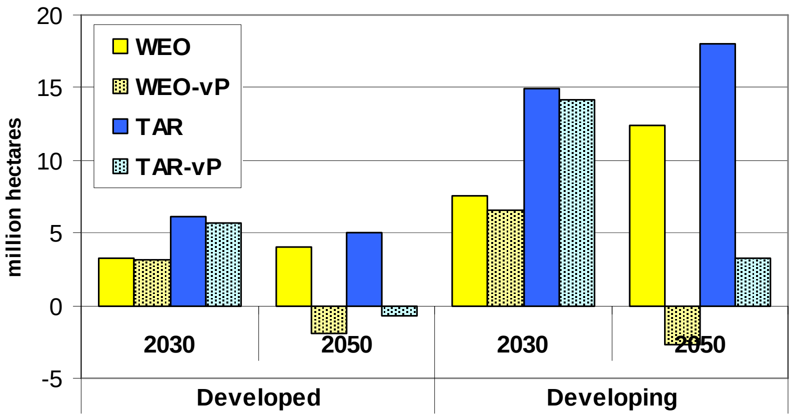


Source: IIASA world food system simulations, ELOBIO scenarios.

Land use

Additional crop productivity growth reduces the amount of arable land expansion. Figure 20 highlights the additional arable land required due to biofuel consumption for the biofuel scenarios WEO and TAR and their variants with higher crop productivity growth WEO-vP and TAR-vP.

Figure 20. Additional arable land required due to biofuel consumption, relative to REF



Source: IIASA world food system simulations, ELOBIO scenarios.

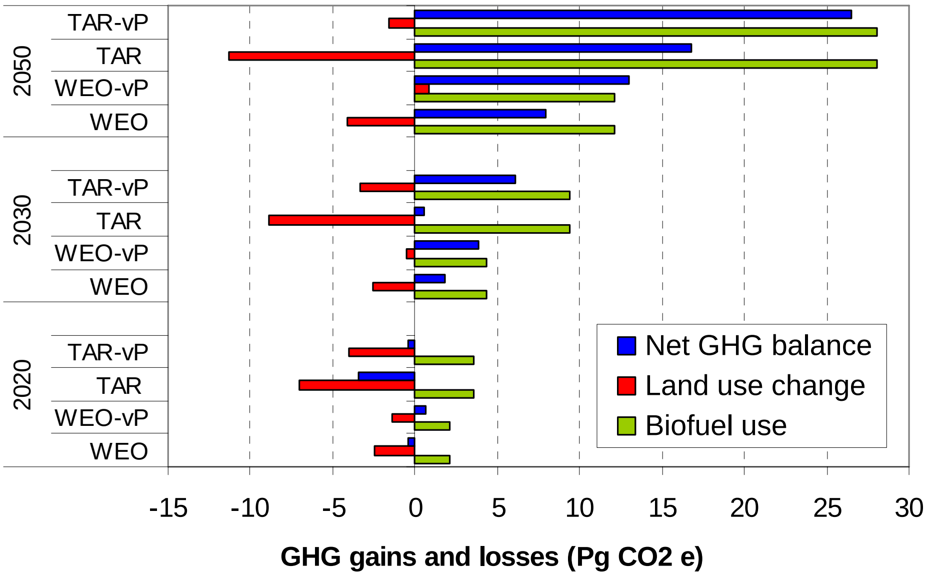
In the short term in 2030, arable land expansion is not much affected by additional productivity growth. In contrast by 2050 the effect of increased productivity result in no or even lower arable land expansion in the scenarios WEO-vP and TAR-vP compared to the reference scenario.

In conclusions, in the longer term the assumed additional productivity growth is high enough to avoid additional land use conversions because of the increased demand due to first generation biofuel feedstock production. In the WEO-vP scenario global arable land requirements are even 5 million hectares lower compared to REF. Lower additional arable land requirements of WEO-vP and TAR-vP compared to WEO and TAR imply less deforestation. By 2050 biofuel consumption causes no additional deforestation in the high agricultural productivity growth scenarios WEO-vP and TAR-vP. Reduced land use conversions have significant implications for GHG balances of the biofuel scenarios.

GHG balance

Cumulative net GHG savings are closely linked to the effects of arable land expansion and subsequent land use conversions. Lower arable land requirements result in less land use conversion and thus in an improved greenhouse gas balances of the biofuel scenarios. Figure 21 shows the accumulated GHG gains (from biofuels use) and losses (from land use changes) for the two biofuel scenarios (WEO and TAR) and their variants with higher crop productivity growth rates (WEO-vP and TAR-vP).

Figure 21. Cumulative net GHG savings of biofuel scenarios



Source: IIASA world food system simulations, ELOBIO scenarios.

Cumulative net GHG savings improve over time. Higher agricultural productivity in developing countries can provide biofuels feedstocks without carbon-intensive land conversion. Therefore scenarios WEO-vP and TAR-vP generally result in higher net GHG savings compared to WEO and TAR. The maximum achievable GHG saving is estimated for the biofuels scenario TAR-vP, where the accumulated savings amount to some 25 Pg CO2 eq., translating into an annual average of 0.5 Pg CO2 eq. The latter represents about 10% of the 2004 global transport fuel emissions.

In the near term (2020) the net emission balance is negative for WEO and TAR and only approximately balanced for WEO-vP and TAR-vP indicating that biofuels deployment cannot deliver the environmental benefits in terms of GHG savings being lower compared to fossil fuel use. However by 2030 all biofuel scenarios show a positive GHG emission balance, which increases further until 2050, especially for the scenarios WEO-vP and TAR-vP, which assume additional crop yield improvements.

Table 1 presents direct and indirect land use emissions for 2020 and 2030 the biofuel scenarios expressed in annualized land use emissions per MJ of biofuel use. We follow the recommendations of the Renewables Directive of the EU (EC, 2009), which states that: “Annualised emissions from carbon stock changes caused by land-use change, el, shall be calculated by dividing total emissions equally over 20 years” (Part C in Annex V). Thus accumulated land use emissions between current and 2020 or 2030 are annualized over 20 years (i.e. divided by 20) and divided by the delta of biofuel use between the reference and the particular biofuel scenario in the year 2020 or 2030.

Table 26. Land use emissions per MJ of biofuel use for different biofuel scenarios calculated for 2020 and 2030

	First generation		**Second generation**		**TOTAL biofuels**		**EU 27** (weighted with EU shares)	
	2020	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
WEO	61.5	46.4	9.6	5.2	58.9	38.0	61.5	41.9
WEO-vP	34.7	8.0	9.6	5.2	33.4	7.4	34.7	7.7
TAR	77.3	73.4	9.3	5.1	58.0	42.5	56.2	41.2
TAR-vP	42.5	24.9	9.3	5.1	33.0	15.9	32.2	15.6

Source: IIASA world food system simulations, ELOBIO scenarios.

ELOBIO results highlight the importance of the time dimension as well as the share of second generation biofuels in assessing biofuel impacts. Speed of first generation biofuel introduction combined with the assumed growth in agricultural productivity determines land use effects and net GHG balances.

5.3 Land use restrictions

Concern is mounting that crop-based biofuels will increase net greenhouse gas emissions if feedstocks are produced by expanding agricultural lands (ILUC ref). This is in particular true when carbon rich environments, such as tropical forests or wetlands, are converted to cropland. Tropical forest clearing has already been observed due to large-scale expansion of soybeans and oilpalm in response to food and feed demands over the last two decades (Koth and Wilcove 2008, Morton et.al 2006) and evidence is mounting that biofuel production has contributed to recent deforestation (Gibbs et.al 2008, Laurance 2007). Analysis of satellite pictures across the tropics shows that between 1980 and 2000, more than half of new cropland came from intact rainforests and another 30 percent from disturbed forests. The FAO is in the process of collecting and interpreting the data for the current decade (Stanford report 2009).

Future crop yield improvements and technology advances, coupled with unconventional petroleum supplies, will increase biofuel carbon offsets, but clearing carbon-rich land still requires several decades or more for carbon payback. No foreseeable changes in agricultural or energy technology will be able to achieve meaningful carbon benefits if crop-based biofuels are produced at the expense of tropical forests (Gibbs et.al 2008).

Gibbs analyzed satellite images taken from 1980 to 2000 to try to answer the question of whether tropical crops are largely being planted on deforested or degraded land. She found that the majority of new crops were planted on freshly deforested rather than degraded land.

The land use component of the biofuel scenario assessment highlights that arable land expansion induced by the additional demand for first generation biofuel feedstocks will likely cause deforestation.

Causes of deforestation are manifold making estimates of deforestation difficult and uncertain. Future forest conversion will depend on the willingness, priorities and capacity of national governments to protect forests and the effectiveness of legislation and other measures taken to reduce deforestation.

Land use restrictions can be applied in the agricultural land conversion module of the modelling framework for testing policy alternatives. Avoiding deforestation induced by expanding arable land is a key priority for limiting the agricultural sectors GHG emissions and safeguarding biodiversity. Provided effective measures for protecting forests could be enforced, arable land can only expand on converted grassland. In regions where limited suitable grassland for arable land expansion exists, forest land conversion restrictions can have effects on prices and trade patterns.

6 CONCLUSIONS

An integrated spatial ecological-economic modelling framework has been applied to assess the impacts of accelerated biofuel consumption on world food markets and the environment. For this purpose two biofuel scenarios, which represent foreseen policies for future biofuel demand, have been compared with a baseline assessment (Scenario REF) portraying a world where biofuel consumption remains at the year 2008 level of consumption. The simulations were carried out on a yearly basis from 1990 to 2050.

The biofuel scenario WEO assumes until 2030 regional biofuel use as projected by World Energy Outlook Reference scenario (WEO 2008) as projected by the International Energy Agency (IEA, 2008) and second-generation conversion technologies becoming commercially available after 2015 and being deployed gradually. A target scenario TAR assumes a fast expansion of biofuel production in accordance with mandatory, voluntary or indicative targets announced by major developed and developing countries and an accelerated deployment of second-generation conversion technologies. Between 2030 and 2050, both biofuel scenarios assume biofuel consumption to increase linearly according to regional per capita biofuel consumptions between 2000 and 2030.

Sensitivity runs highlight (i) the importance of animal feed generated as by-product during biofuel production; (ii) the impact of alternative assumptions on the rate of agricultural productivity growth (Scenarios WEO-vP and TAR-vP); and (iii) implications of land use restrictions. The assumed additional productivity growth rates in the scenarios WEO-vP and TAR-vP are in Sub-Saharan Africa and selected developing countries around 6% in 2025 and 10% and 20% in 2050 depending on region (Table 24).

Impacts on the world food system

The imposed additional biofuel demand causes changes of agricultural prices in the national and international markets, which in turn affects over time investment allocation and labour migration between sectors as well as reallocation of resources.

Biofuel consumption pushes crop prices up but animal feed prices down. Biofuel by-products use as animal feed play an important role for offsetting price increases. The livestock sector generally benefits from biofuels use. The extent of price effects is strongly dependent on assumed agricultural productivity growth rates.

The increased demand for food staples due to the production of first-generation biofuels results in market imbalances and push international prices upwards for all commodities except protein feed and livestock. Crop price increases are in the order of 10 to 20% depending on time, commodity and scenario. Changes in the price index for aggregate agricultural production resulting from accelerated biofuels use are around 7% and 10%-16% for WEO and TAR respectively (Table 15).

The livestock sector is strongly linked to biofuel use because of valuable by-products being generated during biofuel production including livestock feed from starch based ethanol production (DDGS) and protein meals and cakes from crushing oilseeds for biodiesel production. These additional animal feed volumes result in about 30% lower prices for protein feed compared to the reference scenario REF without accelerated biofuel production (Table 15). While in the case of REF prices for livestock products increase up to 17% by 2050, the price dampening effect of DDGS use for animal feed leaves livestock product prices in the biofuel scenarios remaining at approximately similar levels over time (Table 22).

The assumed additional productivity growth rates in developing countries of the sensitivity scenarios WEO-vP and TAR-vP have a strong impact on the price development of agricultural commodities especially after 2030. By then the impact of the productivity growth is apparently stronger than the additional demand for first generation biofuel feedstocks and prices become even lower compared to a situation where neither additional biofuel consumption nor additional productivity growth as assumed in the reference scenario REF.

Risks for food security require enhanced efforts to increase agricultural productivity growth in developing countries and achieve yield gap reductions.

Rising food commodity prices are of particular concern for low income consumers. By 2020 due to the use of first-generation biofuels in the WEO and TAR scenario, an additional 44 million and 94 million people respectively are at risk of hunger. Given that in the reference projection until 2020 already over 800 million at risk of hunger these additional people due to increased biofuel consumption are of particular concern.

Agricultural productivity growth rates in developing countries are central for narrowing yield gaps and improving the region’s competitive position in world’s agricultural markets. After 2030, the anticipated additional productivity growth rates in the scenarios WEO-vP and TAR-vP are sufficiently high to counterbalance increases in hungry people caused by biofuel expansion. In contrast the number of people at risk of hunger even decreases compared to a world without accelerated biofuel deployment by up to 40 million. However the absolute number of people at risk of hunger is still projected at 400 million in 2050 indicating that substantial additional efforts will be required in combating hunger.

Biofuels can enhance rural development. Beneficiaries depend on the regions’ competitive strength.

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 labour. At the same time, consumers react to price increases and adjust their patterns of consumption. In the scenario WEO and TAR production increases in response to higher agricultural prices are stronger in developed countries with subsequent effects on regional development. Throughout the projection period developed countries increase their value added in agriculture substantially more than developing countries and thus benefit relatively more from biofuel deployment. The highest gains are projected for North America peaking in the 1930s with over 6% relative to REF.

In contrast focusing on reducing yield gaps in developing countries, as assumed in WEO-vP and TAR-vP, strengthens the region's competitive position and brings about gains in value added from crop and livestock sector of up to 6%. The higher competition for developed countries reduces their rural development gains from biofuel production.

Impacts on the environment

The required increases in agricultural products are achieved by a combination of increases in productivity on existing arable land and arable land expansion. Land use changes induced by increased biofuel consumption are in the centre of the debate on the benefits of biofuels for climate change and greenhouse gas saving, a prime goal of biofuel use. This study captures both direct and indirect land use changes by modelling responses of consumers and producers to price changes induced by competition of traditional food and feed markets with biofuel feedstock production.

'Low disturbing' biofuel development requires agricultural productivity increases to exceed food, feed and biofuel demand growth.

Arable land expansion to meet growing food and feed demand amounts to about 120 and 170 million hectares by 2030 and 2050. Due to first-generation biofuel feedstock production by 2030 an additional 11 and 22 million hectares will be converted to arable land in the WEO and TAR scenario respectively, representing a net increase in arable land expansion of 9% and 18%. In both biofuel scenarios more than two thirds of the additional arable land expansion occurs in Africa and Latin America.

The use of the ethanol by-product DDGS for animal feed plays an important role in the land use effects of first-generation biofuel consumption. The 'land saving' effect of using DDGS as animal feed is about 7 million hectares, an important improvement for the biofuels greenhouse gas balances.

Without imposing land use restrictions arable land expansion causes deforestation with the inherent consequences of substantial carbon emissions and biodiversity loss. Results indicate that by 2030 biofuel feedstock production may be responsible for up to 9 million hectares of additional deforestation, i.e. a 10% increase compared to a world without biofuel expansion with the majority of additional deforestation occurring in Latin America. Additional deforestation slows significantly after 2030 because of increased uses of second-generation biofuels of up to over 50% in the TAR scenario. It should be noted that feedstocks for second-generation biofuels are assumed to be derived from either waste and residues or ligno-cellulosic feedstocks produced on available pastures and other wooded areas.

Higher yields reduce the amount of arable land expansion. In the longer term (after 2030) the assumed agricultural productivity increases in WEO-vP and TAR-vP are sufficiently high to allow the food, feed and biofuel demand being produced primarily on existing agricultural land and thus avoiding deforestation and other land use conversions.

For GHG benefits to materialize, yield gap reduction in developing countries, carefully monitored speed of biofuel expansion and enforceable land use restrictions, especially avoiding deforestation, is important.

Additional arable land expansion due to first generation biofuel consumption and associated land use conversions may reduce or in the short term or even reverse the greenhouse gas saving effect of biofuel consumption. The net balance of accumulated greenhouse gas savings due to fossil fuel substitution and the cumulated carbon losses resulting from land conversion highlight the importance of the time perspective. For the assessed biofuel scenarios the cumulative net GHG balances are positive only after 2020, i.e. only then the adoption of biofuels (as specified in the scenarios) becomes environmentally friendly in terms of lower GHG emissions compared to the fossil fuels they replace.

GHG savings are generally higher for the scenarios with higher crop productivity due to their lower arable land requirements and less land use conversion. By 2050 a maximum accumulated net GHG savings of some 25 Pg CO2 equivalent could be achieved in the *TAR-vP* scenario. For comparison, in 2004, the global road transport sector produced 4.7 Pg CO_2 emissions.

In terms of land use conversions and GHG savings the scenarios with higher agricultural productivity growth clearly outperforms in the longer term a reference scenario without biofuels.

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Annex 1. National and Regional Models in the WFS

National Models - with country-specific structure

United States, China, India, Former USSR

National Models – common structure but individually estimated

Argentina, Australia, Austria, Brazil, Canada, Egypt, Indonesia, Japan, Kenya, Mexico, New Zealand, Nigeria, Pakistan, Thailand, Turkey, EU-9, Eastern Europe.

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, Zaire, Burundi, Madagascar, Rwanda, Somalia, 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.

Rest of the World: all countries not specified above.

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

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.

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