In•Stream

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1. Introduction

European societies and their policymakers face crucial challenges in the early 21st century: achieving sustainable and environmentally benign economic growth in the context of increasing global competition, improving social equity across countries and social groups within countries, providing reliable, efficient and environmentally benign energy supply, promoting global environmental protection like climate change mitigation, biodiversity preservation, etc. All these challenges are related to one or several aspects of sustainable development: the economic, social and/or environmental pillar. Assessments of the linkages among various components of the three pillars have revealed a range of mutually affirmative as well as conflicting relationships. Linkages even among components of the same pillar can be synergistic or conflicting, as attempts to improve sustainability in one domain can foster or encumber that of others. Moreover, in an increasingly globalizing world, sustainable development strategies in one world region can trigger wide-ranging positive or negative implications for sustainability targets and prospects in others.

It has long been recognized that focusing on aspects of development characterized by mainstream economic indicators can harm the social and environmental components. The main goal of the In-Stream project is to explore the linkages between mainstream economic and sustainable development objectives and the indicators used for characterizing them. A key question in this respect is the costs of sustainability, i.e., what are the economic implications of achieving specific sustainability targets. The objectives related to exploring this question include

- To perform “linking analyses” by assessing economic and other costs of operating the economy under different sustainability constraints using economy-wide models (general equilibrium models).
- To bridge mainstream economic indicators with sustainable development indicators by quantifying impacts of different sustainability indicators on indicators such as GDP and competitiveness.
- To extend models to the sectoral and regional characteristics of several environmental indicators such as land-use and air pollution.
- To test the robustness of results by using sensitivity analysis.

This report contributes to the achievement of the above goals by exploring the linkages among economic and sustainable development aspirations in land-use and agriculture, more specifically in the area of biofuels. Mounting concerns about climate change have increased interest in land-based renewable energy sources. This issue is also an important item in the future of the EU Common Agricultural Policy. The combination of the IIASA World Food System general equilibrium model and the bio-geographical Agro-ecological Zones (AEZ) models provides a convenient tool for analysing all aspects of sustainable development (economic, environmental and socio-economic) in a consistent framework. This increases the policy relevance of sustainability indicators and helps formulate recommendations for environmentally sound agricultural and renewable energy policies.

The agricultural sector is demanded to provide a wide range of goods and services, including food, feed, fibre and bio-energy crops, while preserving environmental resources and protecting nature to achieve long-term sustainability of land and water resources. An improved understanding of the energy-food security-environment linkages requires a spatially detailed assessment of alternative land use and rural development options and strategies.

Based on an integrated agro-ecological and socio-economic spatial global assessment model, this report presents results from an in-depth analysis of the impacts of biofuel developments on the sustainability aspects of food security and climate change by characterizing the main components, input and output streams, assumptions and outcomes by a series of mainstream economic and sustainability indicators. The purpose is to quantify as to what extent improving one sustainability target (mitigating climate change by the expansion of biofuel production) may alter the near-term and long-term sustainability performance measured by other indicators depicting implications for food, agriculture and resource availability.

For the analysis of the global agricultural system, a state-of-the-art ecological-economic modelling framework is applied. It has two major components: the FAO/IIASA Agro-ecological Zone (AEZ) model and the IIASA World Food System (WFS) model. The two main model systems, adapted and expanded for resource use and by-product generation of biofuel production, form the basis of scenario evaluation of the impacts of alternative biofuel deployment pathways 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. An initial baseline assessment serves as 'neutral' point of departure to which alternative biofuel scenarios are compared for assessing their impacts. 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.

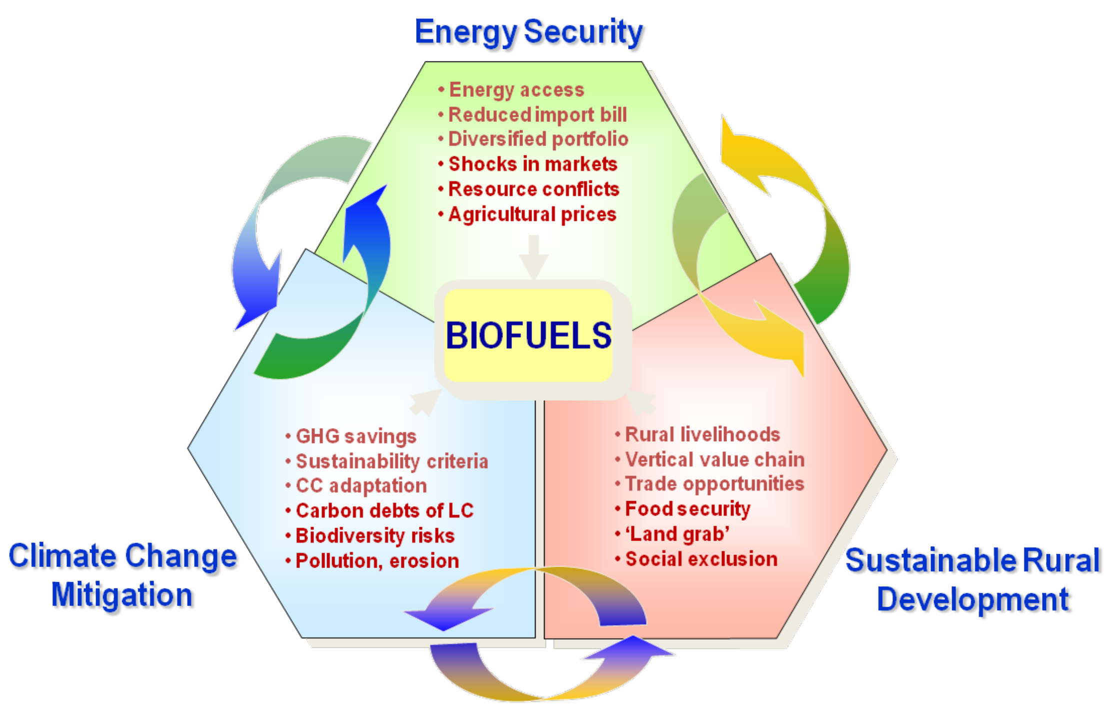
The report is structured as follows: Section 2 presents the analytical framework and the methodological foundations of the study. This is followed by an overview of sustainability issues concerning biofuels in Section 3. In Section 4 the baseline assessment of biofuels is presented, followed by the introduction of the biofuel scenarios, and finally impacts of the expansion of first generation biofuels are presented under a range of scenarios. Section 5 summarizes the linkages between economic and sustainability targets concluded from this assessment.

2. Analytical framework and methodological foundations

2.1. Overview of the assessment framework.

Three key sustainability objectives are involved in pursuing biofuels strategies. Climate change mitigation has become a primary political concern in recent years. GHG emissions from the transport sector are growing fast and biofuels are considered as an important option to reduce the net carbon intensity of the transport sector. A potential co-benefit from using biofuels could be realized by improving energy security. Finally, biofuels present an opportunity to diversify agricultural production, increase incomes and thereby improve rural livelihoods, open additional trade opportunities, etc. The main components of the assessment framework for sustainability scenarios, indicators and policies are presented in Figure 1.

Figure 1: Analytical framework: Biofuels, Food Security, and Climate Change



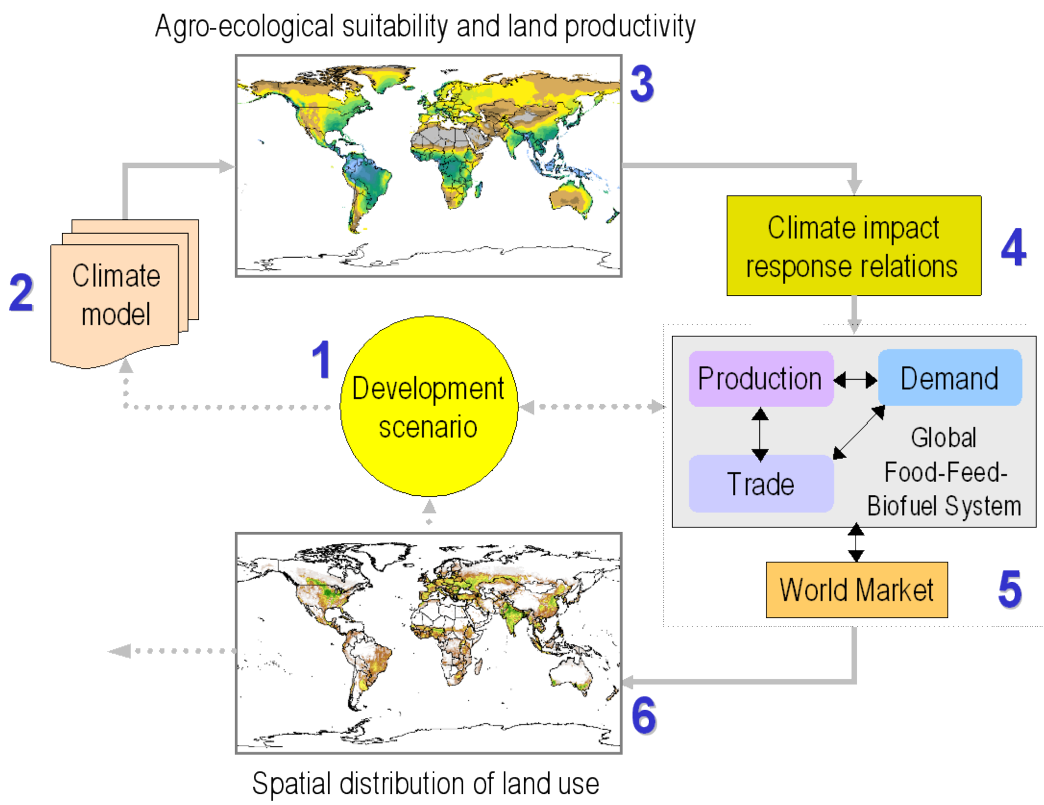
2.2 Methodology and data

2.2.1 Integrated model system overview

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

The study is based on a state-of-the-art ecological-economic modeling approach. The scenario based quantified findings of the study rely on a modeling framework that includes two components: the FAO/IIASA Agro-ecological Zone model and the IIASA global food system model. The modeling framework (see Figure 2) encompasses climate scenarios, agro-ecological zoning information, demographic and socio-economic drivers, as well as production, consumption and world food trade dynamics.

Figure 2 : Framework for ecological-economic world food system analysis



The modeling framework consists of six main elements:

1. A storyline and quantified development scenario (usually chosen from the extensive integrated assessment literature) is selected to delineate the broader socioeconomic development context for the World Food System model, such as demographic changes in each region and projected economic growth in the non-agricultural sectors. The storyline also provides assumptions characterizing in broad terms the international settings (e.g. trade liberalization; international migration) and the priorities regarding technological progress. It quantifies selected environmental variables, e.g. greenhouse gas emissions and atmospheric concentrations of CO_2. In this study it also defines scenarios of demand for first- and second-generation biofuels.

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

3. The agro-ecological zones (AEZ) method takes a climate scenario as input , estimates the likely agronomic impacts of climate change on a spatial grid of 5′ by 5′ latitude/longitude and identifies adaptation options.

4. Estimated spatial climate change impacts on yields for all crops are aggregated and incorporated into the parameterization of the national crop production modules of a regionalized World Food System model.

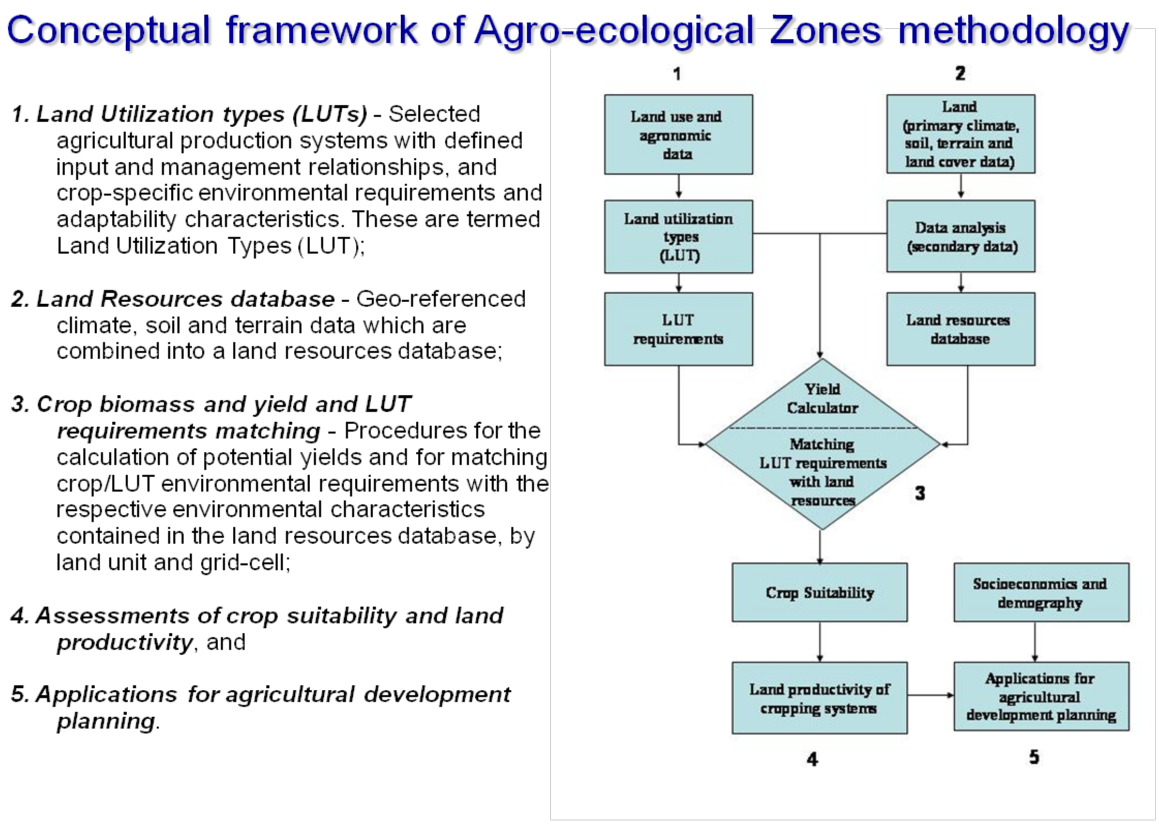
5. The global general equilibrium World Food System model– informed by the development storyline and estimated climate change yield impacts – is used to evaluate internally consistent world food system scenarios.

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

2.2.2 AEZ methodology

The AEZ model uses detailed agronomic-based knowledge to simulate land resources availability, assess farm-level management options and estimate crop production potentials. It employs detailed spatial biophysical and socio-economic datasets to distribute its computations at fine gridded intervals over the entire globe (Fischer et al., 2002a; 2005). This land-resources inventory is used to assess, for specified management conditions and levels of inputs, the suitability of crops in relation to both rain-fed and irrigated conditions, and to quantify expected attainable production of cropping activities relevant to specific agro-ecological contexts. The characterization of land resources includes components of climate, soils, landform, and present land cover. Crop modeling and environmental matching procedures are used to identify crop-specific environmental limitations, under various levels of inputs and management conditions. The model framework is shown in Figure 3.

Figure 3: The AEZ framework



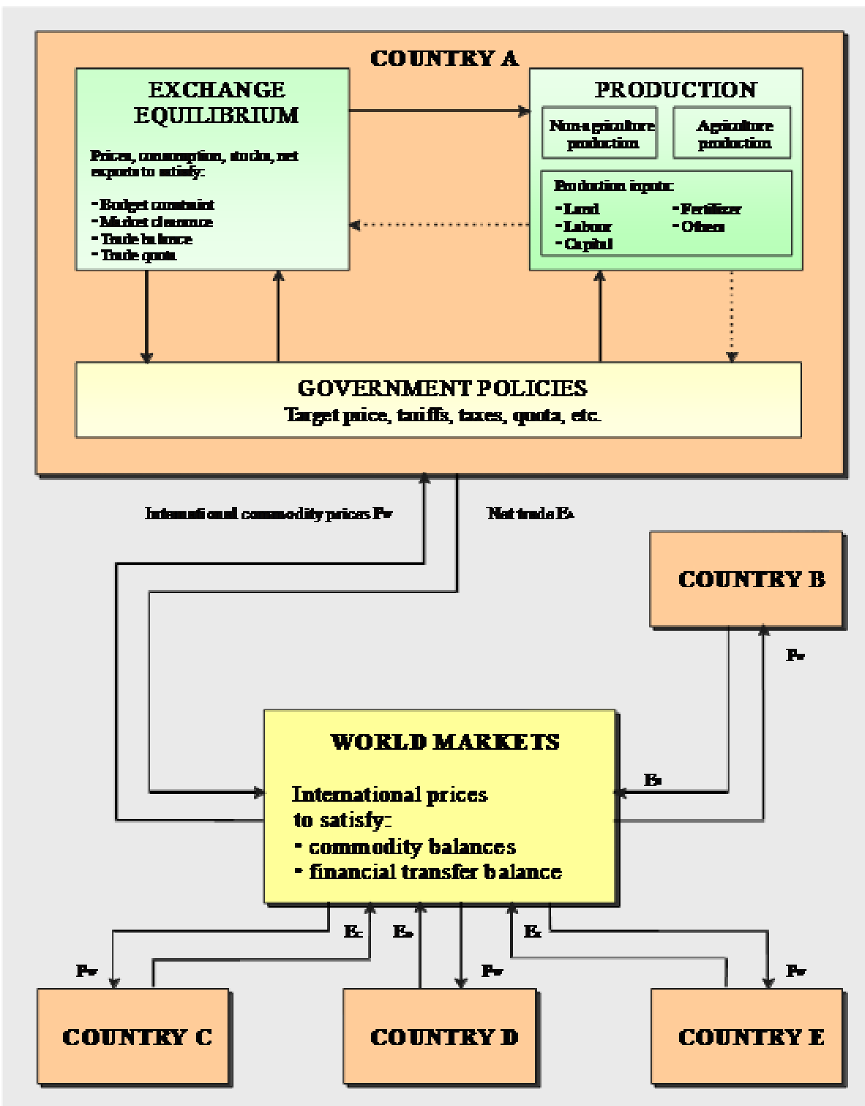
In summary, the AEZ framework contains the following basic elements:

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

2.2.3 World food system model

The World Food System model (see Figure 4) comprises a series of national and regional agricultural economic models. It provides a framework for analyzing the world food system, considering 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.

Figure 4: World Food System Model (WFS)



The World Food System model is an applied general equilibrium (AGE) model system. While focusing on agriculture, this necessitates that also all other economic activities are represented in the model. Financial flows as well as commodity flows within a country and at the international level are kept consistent in the sense that they must balance, by imposing a system of budget constraints and market-clearing conditions. Whatever is produced will be demanded, either for human consumption, feed, biofuel use, or as intermediate input. Alternatively, commodities can be exported or put into storage. Consistency of financial flows is imposed at the level of the economic agents in the model (individual income groups, governments, etc.), at the national as well as the international level. This implies that total expenditures cannot exceed total income from economic activities and from abroad, in the form of financial transfers, minus savings. On a global scale, not more can be spent than what is earned.

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

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

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

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

The IIASA World Food System model has been calibrated and validated over past time windows, it 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, 2007; Fischer et al, 2009).

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 fertilizers), human consumption, use for biofuel production, and commodity trade, value added in agriculture, investments by sector and income by group and/or sector.

2.3 Scenario formulation

The above modelling framework has been applied to study a broad range of policy issues pertaining to the sustainable development of the world's land resources and agriculture. This subsection presents a general description of how to formulate scenarios for use by the models. Table 1 provides a summary of the most important scenario assumptions required for themodel simulations. The first three domains in Table 1 provide the general evolution of key drivers as the foundation for any assessment: socio-economic development, technology and climate change. The last three domains describe features more specific for the formulation of biofuel scenarios.

Table 1: Scenario assumptions for the model simulations

Domain	Type of variables	Source
1. Socio-economic	Population growth GDP growth	UN (2009) FAO (2009)
2. Agricultural technology	Crop yield growth	
3. Climate change	Climate change scenarios	UK Hadley Centre, SRES (B2)
4. Energy and transport	Transport fuel requirements Share of biofuels in total transport fuels Biofuel portfolio (Share of 1st generation)	IEA (2009); EU Commission services
5. Land use restrictions	Permitted land conversions Pattern of conversion	WCMC 2009 GAEZ v3.0 (IIASA/FAO, 2010)
6. Policy assumptions	Taxes, subsidies Border protection	Further gradual reduction of historical protection levels

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 may affect 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; 2009).

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 biofuels that rely on conventional food and feed crops and therefore necessarily compete for agricultural land.

Land use restriction

Demand for food crops, livestock and biofuel feedstocks combined with assumed improvements in agricultural technology determine agricultural land requirements. When the existing cultivated area is insufficient to meet agricultural demand surrounding areas may be converted for agricultural use. Assumptions on magnitude and sources of agricultural land conversion are crucial for agricultural prices and environmental impacts. Expansion of agricultural land into protected areas as defined in the database on protected areas is not permitted in the simulations. Other land use restrictions not generally enforced in the simulations, such as no conversion of forest and wetland to cultivated areas, would have a major 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 is important in the competition for land used for food or energy crops.

Policy assumptions

Subsidies, taxes and border 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.

3. Sustainability issues concerning biofuels

A comprehensive evaluation of the sustainability of biofuel policies needs to cover all three dimensions of sustainable development (economic, social and environmental) based on criteria specifically tailored to the sectors involved (agriculture and energy). Accordingly, the main areas to focus on include:

- Food security: Number of undernourished people, access to and affordability of food in vulnerable countries and for vulnerable social groups in all countries.
- Commodity price development: Changes in prices of commodities that can be used as food or feed as well as for producing biofuels (direct price impacts); changes in prices of all other commodities as a result of shifts in land allocation to different commodities (indirect price impacts).
- Environment: Land use effects as a result of converting earlier non-agricultural areas to cropland for biofuels; the environmental impacts (soils and water) of increased fertilizer use; net GHG savings due to the replacement of fossil fuels by biofuels.
- Socio-economic: Rural income effects of the increased opportunity to deliver output to food and fuel markets; employment effects for rural labor resulting from the shifts in cultivation types and areas.

It follows from the above that scenario simulations produce results in terms of:

- Commodity price effects
- Food consumption effects
- Trade effects
- Agricultural income effects
- Land use effects
- Greenhouse gas savings due to replacing fossil fuels by biofuels.

3.1 Biofuel types and uses

We differentiate between so-called first generation technologies, based 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.

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

In the biofuel production process, depending on the type of feedstock, conversion technology, as well as which parts of the plants are used in the production, substantial amounts of by-products may be generated. These by-products can be used as valuable animal feed, and may either substitute imports of feed or compete with conventional domestic feed sources, therefore both trade and domestic feed markets may be strongly affected.

The animal feed industry has productively utilized the by-products generated in the process of converting oilseeds into higher value food material and more recently into biodiesel. In the case of soybean, the protein rich soymeal rather than oil is usually the prime reason for soybean production.

The alcohol-free solids and liquids remaining after fermentation and distillation of starchy crops 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 at 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 in the model simulations that with further expansion of biofuel production by 2020 all DDGS produced will enter commodity markets and be available as feed supply domestically or via international trade.

Five main groups of land utilization types with specific biofuel production pathways are distinguished in the modelling framework, 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 biofuel feedstocks.

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.

To quantify impacts of alternative biofuel scenario variants on main agricultural commodity and factor markets, results are presented relative to reference conditions for a scenario without additional biofuel expansion beyond 2008 levels. 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 impact indicators (e.g. fertilizer use, cultivated land expansion, additional deforestation).

3.2 Biofuel products

Biofuels include solid, liquid, or gaseous fuels that can be produced from biomass material. The biofuels industry currently comprises two distinct sectors - ethanol and biodiesel - that can be blended with fossil gasoline and diesel, respectively. Current biofuel production processes rely on first generation conversion pathways based on sugar, starch, or vegetable oil components of feedstocks.

Although biofuels are made from crop plant material, and hence are a renewable source, they may not be as ‘green’ as they seem. To produce biofuels, large amounts of land are required for feedstock cultivation. Irrigation, use of fertilizers, transportation, conversion, and refinery processes all require energy input and emit carbon dioxide. There is a large number of lifecycle analysis studies that suggest that current biofuels save little greenhouse gas (especially when also considering associated land use changes) and that production of biofuels may pose a threat to biodiversity and food security.

Ethanol is produced through the fermentation of carbohydrates. Any crop that contains a high starch or sugar content can be used. Main feedstocks are maize, wheat, sugar cane, and sugar beet, and starchy food crops like cassava.

Biodiesel is produced through a chemical process called transesterification of vegetable oils. Main feedstocks are rapeseed, soya bean, and oil palm. Jatropha has been promoted as a valuable feedstock because of the assumed ability to produce in marginal and low rainfall areas.

Biofuel production from starch, sugar, and vegetable oil can rely on well-established technologies. The rapid deployment of first-generation feedstocks in Europe recently reflects favorable adoption rates of the agricultural sector to feedstock production. Farm technology requires minimum adaptation as farmers are familiar with these crops and can easily integrate energy crops into their food and feed crop rotation patterns. Decentralized processing plants and feedstock production sites have proved to be feasible.

Environmental concerns raised with regard to biofuel production include the high intensity of feedstock cultivation, unregulated deforestation, and the intensive use of fertilizers and pesticides. In addition, crop production and conversion to biofuels requires varying amounts of fossil energy. First-generation pathways reduce greenhouse gas emissions from ‘well-to-wheels’ in the range of 20–70 percent compared with fossil fuels. With the exception of Brazilian sugarcane ethanol, greenhouse gas savings of more than 50 percent are rare.

New, more efficient ***second-generation technologies*** have the potential to expand substantially the feedstock base for biofuel production (e.g., lignocellulosic biomass, non-edible vegetable oils, and algae). Second-generation technologies are of interest due to their lower CO_2 emissions, the possible cultivation on non-food and marginal land, and the possibility of using non-food feedstocks, such as residues and by-products from agriculture and forestry, and from dedicated non-food related feedstocks (e.g. woody and herbaceous plants such as perennial grasses and fast growing tree species). Conversion technologies are still expensive and small-scale and it is estimated that second-generation biofuels may only be commercially available in the next 10 to 20 years.

A number of studies (e.g., OECD, 2008; FAO, 2008a) have highlighted that government support of biofuel production in OECD countries is costly, has limited impact on reducing greenhouse gases and improving energy security, and has a significant impact on world food prices.

3.3 EU sustainability criteria for biofuels

As biofuels gain market share and international trade of biomass, raw materials and biofuels expands, the need to ensure socio-economic sustainability along the whole supply chain becomes more pressing. This includes aspects such as land use, agricultural practices, competition with food uses of crops, energy efficiency and GHG emissions, life cycle analysis (LCA), etc.

Sustainability of a given biofuel needs to be guaranteed in a transparent way. This is only possible if appropriate policy measures influencing and steering the overall supply chain are adopted. A strategy to ascertain sustainability includes the need for monitoring and certification systems.

The Directive on renewable energy (EC, 2009) sets out sustainability criteria for biofuels in its articles 17, 18 and 19. These criteria are related to greenhouse gas savings, land with high biodiversity value, land with high carbon stock and agro-environmental practices. The criteria apply since December 2010. The Commission has adopted a number of decisions and Communications to assist the implementation of the EU's sustainability criteria.

4. Sustainability assessment of biofuels

Worldwide production of biofuels has been growing rapidly over the last decade and reached 45 Mtoe in 2008. Ethanol accounted 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). This section explores the implications of continued or even accelerated growth of biofuel production for several aspects of sustainable development.

4.1 Assessing key outcomes

The environmental benefits of increased biofuel deployment and their contribution to sustainable development have been debated widely in recent years. This subsection specifies the assessment processes for two key environmental aspects of biofuel expansion.

4.1.1 Assessment process for land use changes

All scenario runs projecting world food system development (Fischer et al., 2009) indicate that additional global food and feed demand will largely be met through yield increases and intensification but will also require some additional land to be used for cultivation, notably in developing countries. Depending on the required biofuel quantity, speed of introduction, and biofuel portfolio, additional cultivated land will also be required for biofuel feedstock production. As land conversion, notably deforestation, is critically important for greenhouse gas emissions and impacts on biodiversity, it is explicitly modelled in the integrated assessment framework.

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, except where otherwise indicated.

4.1.2 Assessment process for greenhouse gas savings

An important reason for the adoption of biofuels is that they are considered more environmentally friendly compared to fossil fuels in terms of greenhouse gas (GHG) emissions . 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 users, 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, although not directly causing land conversions, may displace food or feed production to environmentally sensitive areas – a process much debated and referred to as indirect land use changes. 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 use an applied general equilibrium approach to capture direct and 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 accounts for land use changes and production intensification on existing agricultural land as well as consumer responses to changing prices and availability of commodities simultaneously in an internally consistent manner.

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 based ethanol, 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 in a reference scenario without additional biofuel use. Note that this comparison includes both direct and indirect land use changes. 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 and 2000-2030.

4.2 Baseline assessment

4.2.1 Overview

The primary role of the 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 2030.

Population: In the long run, the increase of demand for agricultural products is largely driven by population and economic growth, both mainly in developing countries. Over the next two decades world population growth is projected at about 1%/year with most of the increase in developing countries. Population increase is an exogenous input to the model analysis. The most recent available UN population projections (United Nations, 2009) were used as summarized in Table 2.

Economic growth: Economic performance in the baseline projection REF is shown in Table 3. 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 (FAO, 2006) based on information provided by the agriculture study group at FAO (May 2009; J. Bruinsma, 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.

Table 2: Population development, 2000-2030

	Total population (millions)			
	2000	**2010**	**2020**	**2030**
North America	306	337	367	392
Europe & Russia	752	762	766	761
Pacific OECD	150	153	152	148
Africa, sub-Saharan	655	842	1056	1281
Latin America	505	574	638	1633
Middle East & N. Africa	303	370	442	2553
Asia, East	1402	1500	1584	689
Asia, South/Southeast	1765	2056	2328	511
Rest of World	210	233	249	262
Developed	1141	1177	1202	1211
Developing	4696	5417	6132	6758
Rest of World	210	233	249	262
World	6047	6827	7582	8231

Source: IIASA World Food System reference scenario (REF) simulations, June 2010.

Table 3: Growth of GDP, 2000-2030

	GDP (billion US $ at constant 1990 prices)				Annual growth (%)	
	2000	**2010**	**2020**	**2030**	2000-2020	2020-2030
North America	8287	10582	12389	13706	2.0	1.0
Europe & Russia	7502	9486	11617	14040	2.2	1.9
Pacific OECD	3795	4304	4782	5176	1.2	0.8
Africa, sub-Saharan	238	350	532	809	4.1	4.3
Latin America	1449	2015	2828	4284	3.4	4.2
Middle East & N. Africa	597	850	1212	1773	3.6	3.9
Asia, East	1596	4165	8037	13106	8.4	5.0
Asia, South/Southeast	1255	2021	3138	4843	4.7	4.4
Rest of World	2418	3000	3640	4342	2.1	1.8
Developed	19583	24372	28788	32921	1.9	1.4
Developing	5135	9401	15747	24816	5.8	4.7
Rest of World	2418	3000	3640	4342	2.1	1.8
World	27136	36773	48175	62079	2.9	2.6

Source: IIASA World Food System reference scenario (REF) simulations, June 2010.

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 scenarios of greenhouse gas emissions and associated 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 B2 emissions pathway (IPCC, 2000). Results take into account effects of CO2 fertilization and quantify outcomes with full adaptation of crop types. While the chosen climate scenario is only one of many climate projections available in the literature, note that unfolding of these scenarios and large differences among projections occur only well beyond 2030. Using a wide range of climate scenarios was therefore not considered as important for the assessment of the impact of biofuel expansion to 2030.

Agricultural productivity: In the WFS, crop yield is the result of input use (a function of fertilizer application) and a technology growth factor. Fertilizer use is endogenous, depending on relative prices. The technology factor is exogenously determined by region and crop type with sources derived from FAO's projections and selected country studies.

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 by 2020. Depending on the country, the transmission of changes in world prices to domestic farm gate price levels is either based on econometrically estimated price transmission functions or on fixed protection factors.

Land use restrictions: Expansion of cultivated land is not permitted in protected areas as defined in the AEZ land resources database).

Biofuels: The baseline scenario (REF) assumes historical biofuel development unit 2008 and keeps crop feedstock demand constant after 2008.

4.2.2 Agriculture demand and production

Crop production is the result of 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.

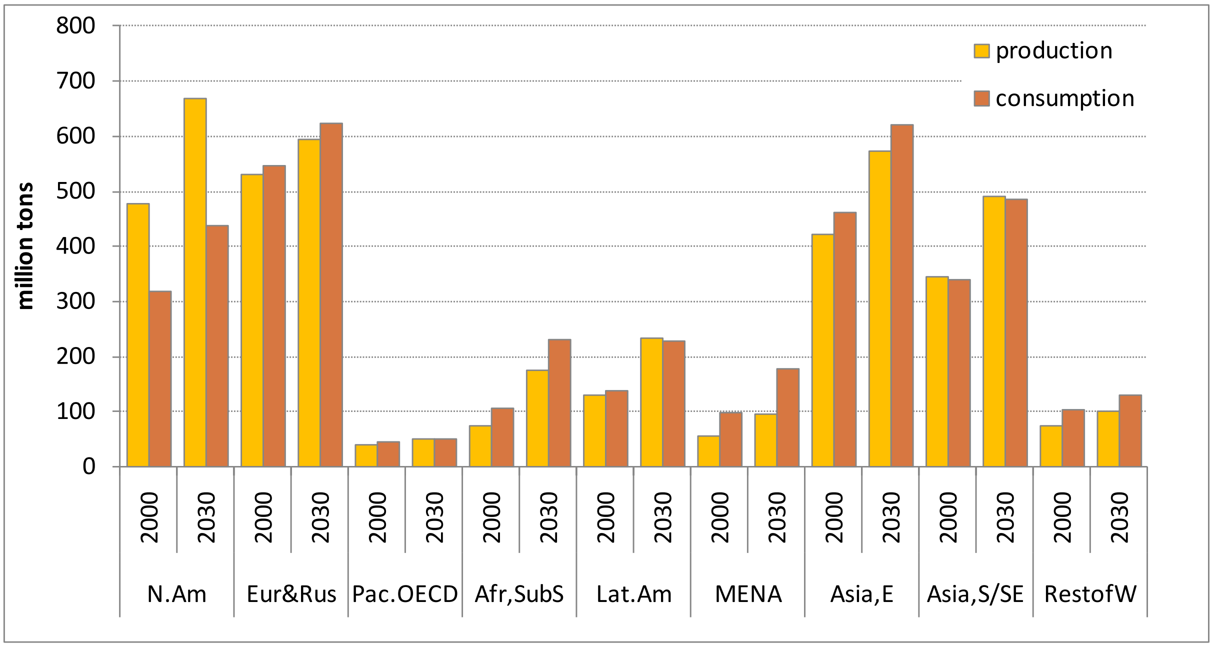
With still considerable population growth in the reference projections, cereal demand continues to grow and production increases from 2.1 billion tons in 2000 to 2.7 billion tons in 2020, and nearly 3.0 billion tons in 2030 (Table 4, Figure 5).

Table 4: Total cereal production and consumption, Scenario REF

REF	Cereal production (million tons)			Cereal consumption (million tons)		
	2000	**2020**	**2030**	**2000**	**2020**	**2030**
Developed	1014	1210	1272	871	1017	1058
Developing	1061	1430	1609	1180	1595	1798
Rest of World	75	93	102	103	122	130
World	2150	2733	2984	2154	2734	2985

Source: IIASA World Food System reference scenario (REF) simulations, June 2010.

Figure 5: Total cereal production and consumption, Scenario REF



As the share of developing countries in global consumption increases from 55 percent in 2000 to 60 percent in 2030 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 188 million tons in 2030. North America is by far the largest net exporter of cereals with about a third of its production being exported to the world market.

At the global level total cereal consumption in 2008 comprised of 47% human food use, 39% animal feed, 3% biofuels and the remainder of 11% is seed and waste. However there are large differences in cereal use between developed and developing countries. While in the developed world the majority of cereals is used as livestock feed (60%), in the developing world the main use is for direct human consumption (two-thirds) and only a quarter is used as livestock feed.

In developed countries the use of cereals for biofuels amounts to 7.5% in 2008 and decreases to 6.9% in 2030 in the reference scenario, which assumes biofuel consumption fixed at the 2008 level. In comparison, the use of cereals for biofuels in 2008 was negligible in developing countries.

4.2.3 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: slowing demographic growth; technological development and growing input use in agriculture, notably substantial increases 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 170% during the period 2002 to 2008 primarily a result of increased demand for cereals and oilseeds for biofuels, low world food stocks, reduced harvests in some locations, for example in Australia due to drought conditions, record petroleum and fertilizer prices, and to some degree market speculations. The food price index decreased somewhat in 2009 but reached the highest ever recorded level at the beginning of 2011.

The baseline projection of scenario REF is characterized by modest increases of world market prices during 2000 to 2030. Table 5 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.[1]

Table 5: Agricultural prices as simulated in scenario REF

	Price Index (1990=100)		
Commodity group	**2000**	**2020**	**2030**
Crops	92	93	97
Cereals	94	104	108
Other crops	91	88	92
Livestock products	102	105	108
Agriculture	95	97	100
Wheat	88	116	119
Rice	97	95	99
Coarse grains	97	104	109
Bovine & ovine meat	107	106	110
Dairy products	97	104	109
Other meat	102	106	109
Protein feed	108	115	121
Other food	90	87	91
Non-food crops	80	76	82

Source: IIASA World Food System reference scenario (REF) simulations, June 2010.

4.2.4 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 47 percent in the 30-year period to 2030, i.e. an annual increase of 1.3%.

The right part of Table 6 highlights the development of percentage of agriculture in total GDP, which decreases on a global level from 5% in 2000 to 3% in 2030. Scenario REF projects also a strong decline of

[1] 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.

agriculture contribution to total GDP in the developing world from 15% in 2000 to 5% in 2030, mainly due to a strong anticipated growth of the non-agricultural sectors in the largest Asian economies.

Table 6: 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	2020	2030	2000-2020	2020-2030	2000	2020	2030
North America	168	200	210	0.9	0.5	2.0	1.6	1.5
Europe & Russia	207	237	251	0.7	0.6	2.8	2.0	1.8
Pacific OECD	47	57	62	1.0	0.8	1.2	1.2	1.2
Africa, sub-Saharan	65	106	135	2.5	2.4	27.2	20.0	16.7
Latin America	155	232	269	2.0	1.5	10.7	8.2	6.3
Middle East & N. Africa	54	86	103	2.3	1.8	9.1	7.1	5.8
Asia, East	249	315	343	1.2	0.9	15.6	3.9	2.6
Asia, South/Southeast	252	352	403	1.7	1.4	20.1	11.2	8.3
Rest of World	64	77	84	0.9	0.9	2.7	2.1	1.9
Developed	422	494	523	0.8	0.6	2.2	1.7	1.6
Developing	776	1092	1253	1.7	1.4	15.1	6.9	5.0
Rest of World	64	77	84	0.9	0.9	2.7	2.1	1.9
World	1262	1663	1860	1.4	1.1	4.7	3.5	3.0

Source: IIASA World Food System reference scenario (REF) simulations, June 2010.

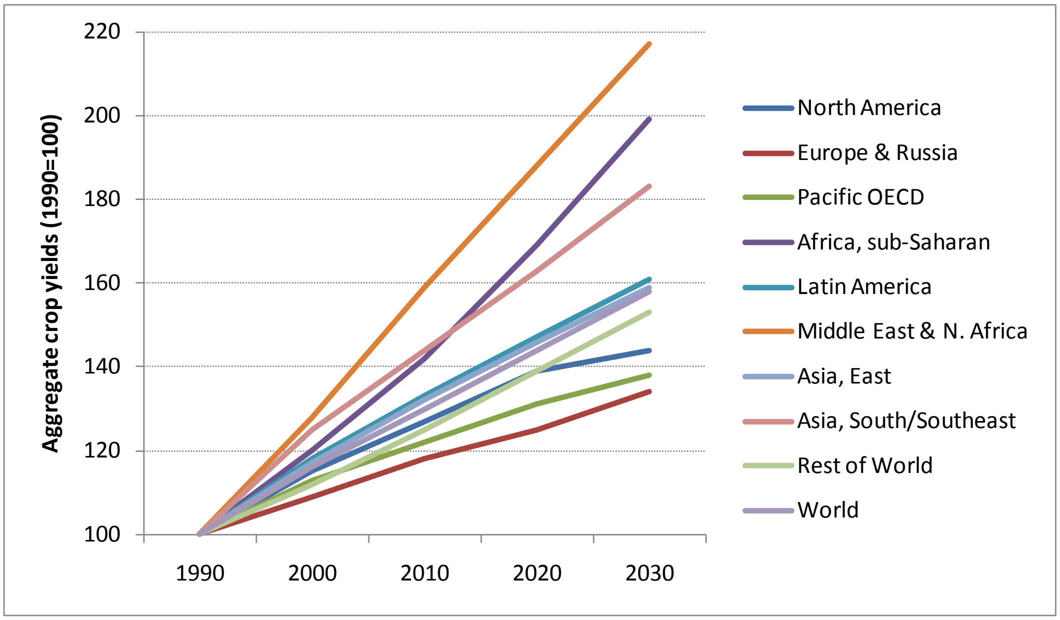
4.2.5 Agricultural productivity

Agricultural productivity depends on available technology and objectives and quality of management. The latter includes input use, cropping patterns and cropping intensity and is determined by farmers' socio-economic conditions.

Agricultural productivity in the WFS is a function of input use (approximated by fertilizer application levels) and a technology factor. Fertilizer use is endogenously determined depending on relative crop output and input prices. The technology factor is exogenously determined by region and crop type with sources derived from FAO's projections and selected country studies. Due to lack of widely accepted available empirical estimates, the model does not consider induced technological progress; instead some additional sensitivity analysis of technological progress assumptions has been conducted.

Describing overall agricultural productivity for regions or countries requires aggregation, which has been achieved in WFS by multiplication with international price weights. Aggregate yields describe a country's crop production volume per unit of arable land. In the scenario *REF* aggregate yields are projected to increase by 67% and 37% in developing and developed countries, respectively, between 1990 and 2030 (Figure 6). Note that these increases result from a combination of increased input use, technological progress and increased cropland intensity (i.e., increased use of physical cultivated land per year through reduced fallow periods and/or increased multi-cropping.

Figure 6: Aggregate crop yields, Scenario REF



Source: IIASA World Food System reference scenario (REF) simulations, June 2010.

Globally cropping intensity increases from 84 percent in 2000 to 90 percent in 2030. In parts of East, South and Southeast Asia the warm climate, sufficient moisture supply and intensive agricultural management allow more than one harvest each year. In other regions, notably Oceania, substantial fallow periods are required for sustainable production resulting on average in less than one harvest per hectare of arable land.

4.2.6 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 most of 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 118 million ha during 2000 to 2030. While aggregate arable land use in developed countries remains fairly stable, 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 7, Figure 7).

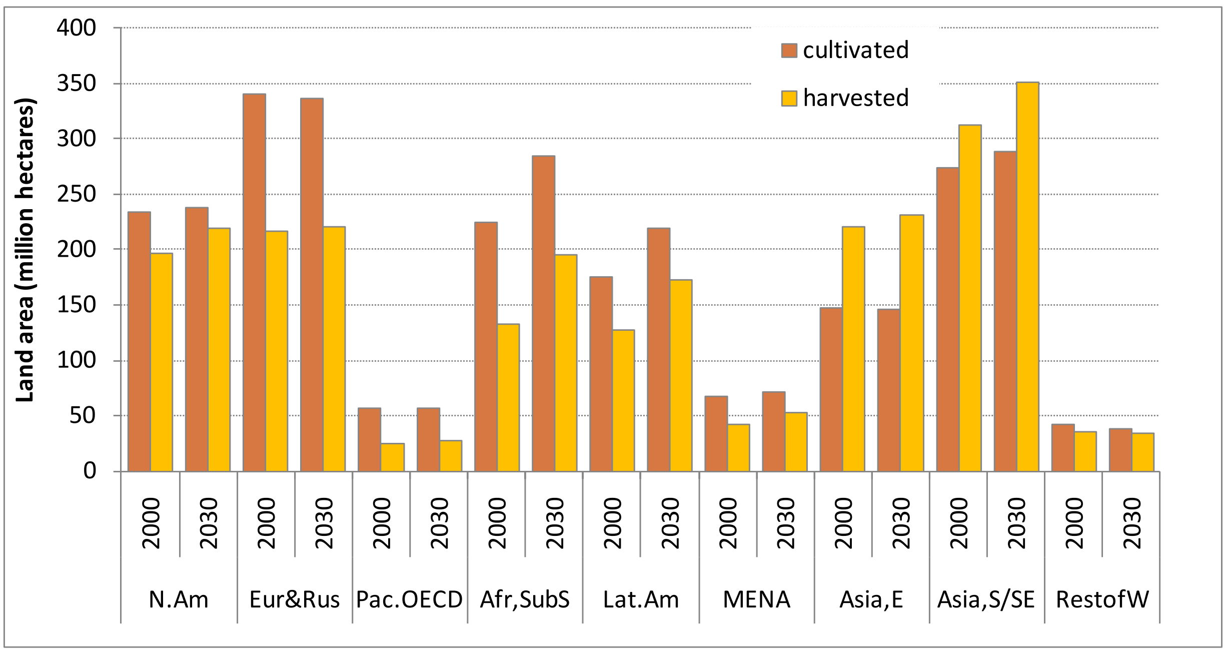
Cultivated land represents the physical amount of land used for crop production. In practice, part of the land is left idle or fallow, and part of the cultivated land is used to produce multiple crops within one year. The total harvested area is shown in the right part of Table 7. The implied cropping intensity (defined as the ratio of harvested over (physical) arable land) increases from about 84 percent in 2000 to 90 percent in 2030 albeit with large regional differences.

Table 7: Cultivated land and harvested area, Scenario REF

Scenario REF	Million hectares					
	Cultivated land			Harvested area		
	2000	2020	2030	2000	2020	2030
Developed	605	604	605	422	443	451
Developing	915	1004	1038	850	971	1019
Rest of World	42	40	38	35	35	34
World	1562	1647	1681	1307	1448	1505
expansion		85	119		141	198

Source: IIASA World Food System reference scenario (REF) simulations, June 2010.

Figure 7: Cultivated land and harvested area, Scenario REF



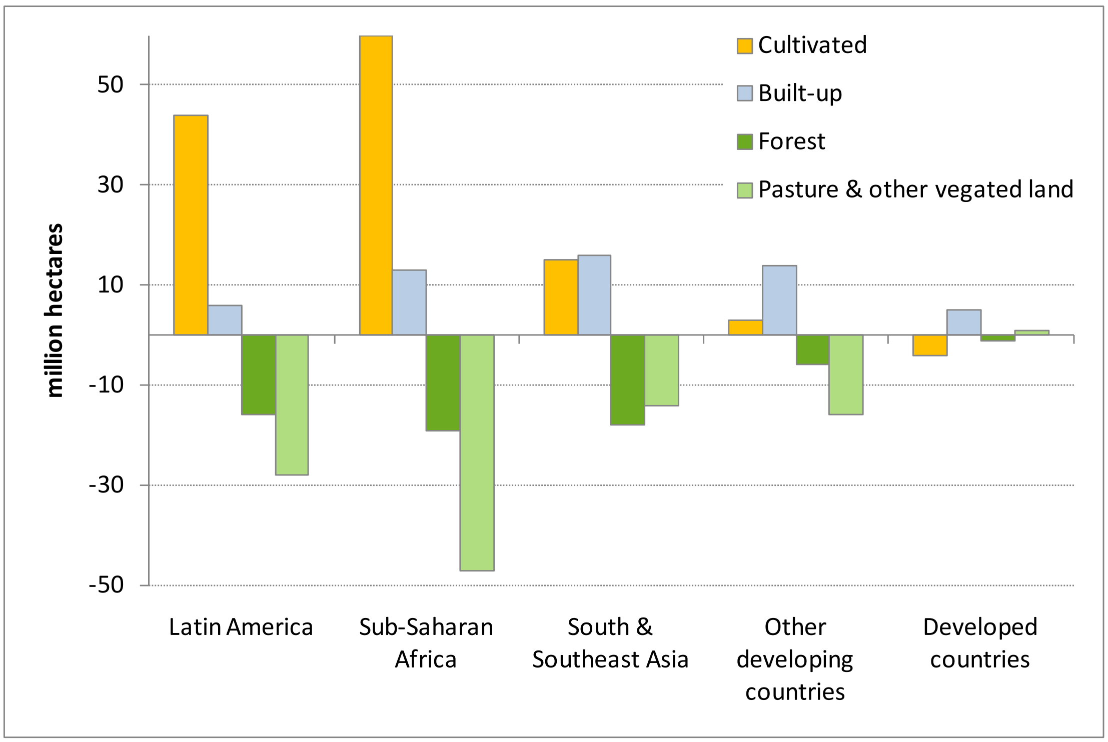
4.2.7 Land use trends

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 uses of a growing population. Both cropland and built-up areas increase at the expense of forest, pasture and other vegetated land. Figure 8 shows for the reference scenario the changes in land use between 2000 and 2030. The vast majority of land use conversion occurs in developing countries with the largest changes occurring in Latin America and Sub-Saharan Africa.

When applying no specific additional land use restrictions, except preserving current areas designated as protected, an estimated 60 million hectares will be deforested during 2000 to 2030 for cropland and built-up areas. Another 104 million hectares pasture and other vegetated areas will be converted to meet demand in scenario REF for cropland and built-up areas.

For example simulated average annual deforestation rates due to agricultural land demand and urbanization amount to 2.1 million hectares between 2000 and 2020 and decrease to 1.8 million hectares in the period 2020 to 2030. For comparison, the historical rate of annual net deforestation in the 1990s was estimated by FAO at 8.3 million hectares and for the first decade of this century at 5.2 million hectares. (FAO, 2010).

Figure 8: Changes in land use between 2000 and 2030, Scenario REF



Source: IIASA World Food System reference scenario (REF) simulations, June 2010.

4.3. Biofuel scenarios

4.3.1 Scenario specifications

The specification of biofuel scenarios included 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, explicit assumptions were made as to the role and dynamics of second-generation biofuel production technologies in each scenario, or conversely, about 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.).

Step 1: Future projections of transport fuel use

For describing regional energy futures we used the World Energy Outlook 2009 reference scenario compiled and published by the International Energy Agency (IEA, 2009). In this scenario, world primary energy demand grows by 1.5% per year on average for 2007-2030, from 12,013 Mtoe to 16,790 Mtoe. This projection embodies the effects of government policies and measures that were enacted or adopted up to mid-2009 (IEA, 2009).

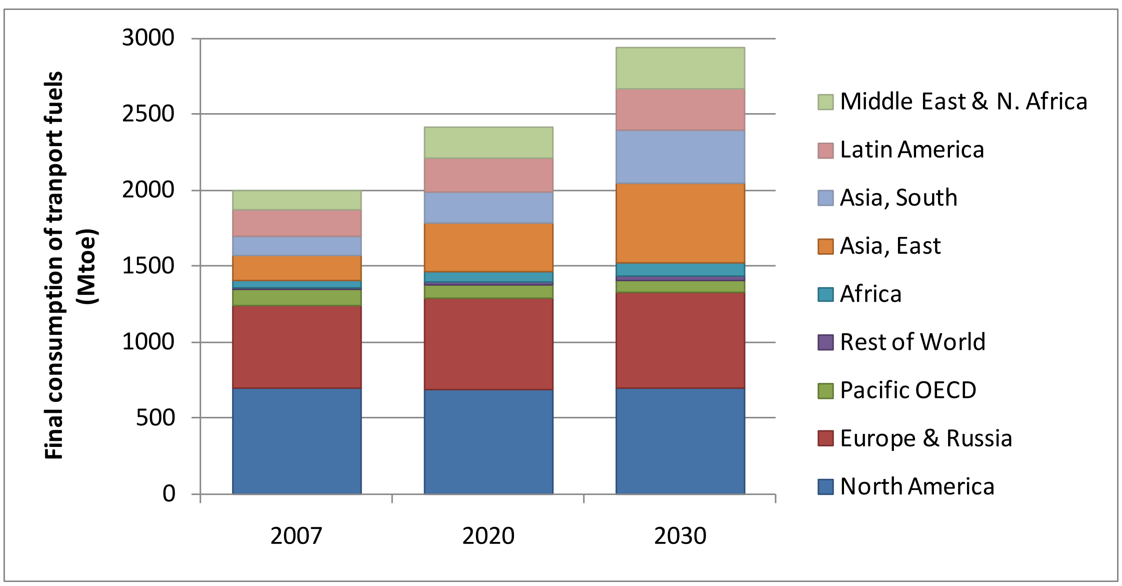
In terms of total final consumption of transport fuel the scenario projects an increase from 2297 Mtoe to 3331 Mtoe for the period 2007-2030. Regional totals of transport fuel consumption derived from the WEO reference scenario for the period 2007 to 2030 are summarized in Table 8 and Figure 9.

Table 8: Final consumption of transport fuels by region

	Million tons oil equivalent (Mtoe)		
	2007	**2020**	**2030**
Developed	1302	1327	1351
Developing	692	1086	1583
World*	2297	2753	3331

* World totals include international marine bunkers and international aviation (Source: IEA, 2009).

Figure 9: Final consumption of transport fuels by region (Source: IEA, 2009).



Step 2: Pathways for biofuel consumption

The *WEO* scenario assumes final consumption of biofuels to reach some 104 million tons in 2020 and to climb to 133 million tons by 2030. In 2007 about 70% of biofuels was consumed in developed countries. This share reduces to 66% in 2020 and further declines to 57% in 2030. The United States and EU-27 account for about 90% of the biofuel use in developed countries.

Amongst the developing countries Brazil has pioneered biofuel production, 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 6 Mtoe in 2000, increases to 36 Mtoe by 2020, and reaches nearly 60 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.

In the developed world, the projected share of biofuel consumption in total transport fuels use in 2020 amounts to 5.4% in the WEO scenario. By 2030 this share increases to 5.8%. For the developing world the scenario projects a biofuels share in total transport fuel use in 2020 and 2030 at 3.4% and 3.8% respectively. At the global level this share comes to 4.5% in 2020 and 4.7% in 2030.

Step 3: Deployment of 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.

Our WEO-based biofuel scenario *(WEO-2009)* assumes that second-generation biofuel technologies will be available in the United States for commercial deployment as of 2015 and by 2030 this share will increase to about 30 percent (see Table 9). The largest biofuel consumers in WEO among developing countries (Brazil, China and India) will also start using second-generation technologies in 2020, but deployment will follow a somewhat slower path to contribute on average 5 percent of biofuels in 2030.

At the aggregate global level, second-generation biofuel shares in scenario *WEO-2009* are 10 percent and 14 percent in 2020 and 2030 respectively.

Table 9: Final consumption of transport biofuels in WEO-2009

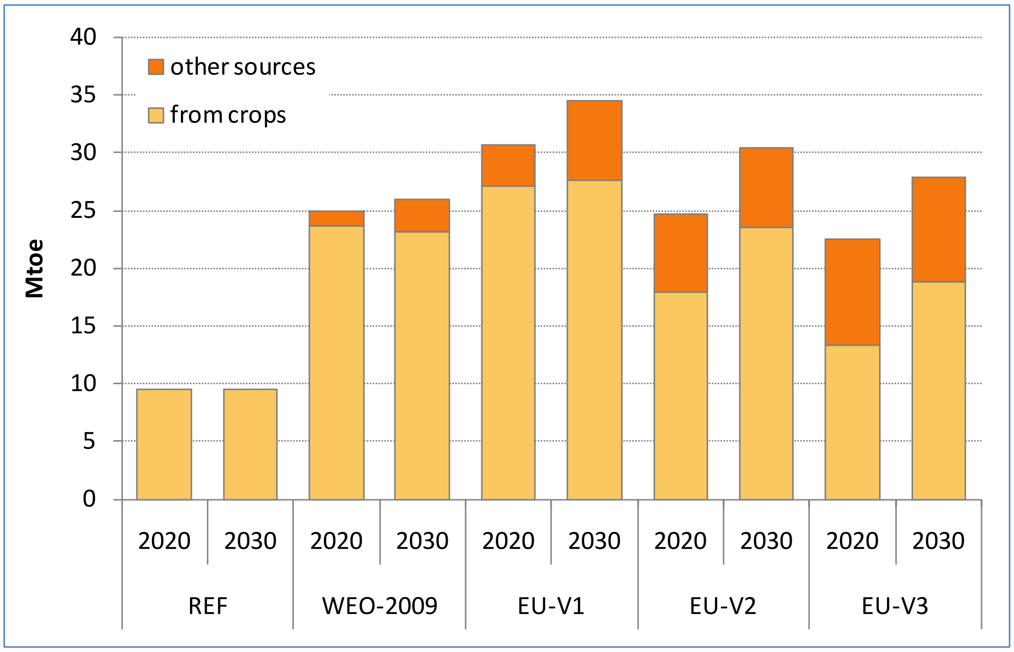
	Million tons of oil equivalent				
	2007	2020		2030	
	Total renewable transport fuels	Total renewable transport fuels	of which from crops	Total renewable transport fuels	of which from crops
North America	15.0	41.7	32.4	46.6	33.5
Europe & Russia	8.8	29.0	27.7	31.9	28.5
Pacific OECD	0.1	0.4	0.4	0.4	0.3
Africa, sub-Saharan	0.0	0.8	0.8	1.2	1.2
Latin America	8.9	20.2	20.2	28.3	26.9
Middle East & N. Africa	0.0	0.1	0.1	1.3	1.3
Asia, East	1.0	7.7	7.7	14.1	13.4
Asia, South/Southeast	0.0	7.3	7.3	13.7	13.0
Rest of World	0.0	0.4	0.4	0.8	0.8
Developed	23.9	71.1	60.4	78.5	62.1
Developing	10.0	36.5	36.5	59.8	57.0
World	33.8	107.6	96.9	138.3	119.1

Source: IIASA World Food System reference scenario simulations, June 2010 based on IEA (2009).

4.3.2 First-generation biofuel feedstocks demanded in the biofuel scenarios

While in the reference scenario *REF* the amount of biofuels consumed in 2008 is kept constant for the entire remaining simulation period to 2030, the amounts increase in the *WEO-2009* and EU-specific scenario variants EU-V1 (pessimistic assumption for electric road transport and second-generation biofuels), EU-V2 (optimistic assumption for electric road transport, intermediate assumption for second-generation biofuels), and scenario variant EU-V3 (optimistic assumption for electric road transport and second-generation biofuels). Transport biofuel use in the EU-27 for four biofuel scenarios is shown in Figure 10.

Figure 10: Scenarios of transport fuels from renewable sources in EU-27



Source: IIASA World Food System scenario simulations, June 2010.

The amount of cereals, vegetable oil, and sugar plants (included in the category 'Other food') required for transport biofuel production in 2020 and 2030 in the different scenarios is shown in Table 10.

Table 10: Global use of agricultural commodities for biofuel production

Scenario	**Cereals** (million tons)		**Other food** (million tons sugarcane equiv.)		**Vegetable oil** (million tons)	
	2020	**2030**	**2020**	**2030**	**2020**	**2030**
REF	78	78	375	375	11	11
WEO-2009	173	203	983	1336	30	36
EU-V1	178	211	1001	1367	33	39
EU-V2	167	197	961	1317	26	33
EU-V3	160	187	932	1281	21	28

Source: IIASA World Food System scenario simulations, June 2010.

4.4 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 also of great concern to developing countries where more than 70 percent of the poor reside in rural areas.

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, often well beyond the national setting of domestic biofuels targets.

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 savings varies widely for individual biofuel production chains. Calculation of GHG savings potentials are further complicated by consideration of indirect land use changes, i.e. displacement effects such as agricultural expansion induced elsewhere by bio-energy feedstock production. 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 the analysis considering four alternative biofuel scenarios, namely WEO-2009, EU-V1, EU-V2, EU-V3.

4.4.1 Economic impacts

The evaluation of the impacts of additional crop 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 alternative biofuel scenario variants to a reference projection (*REF*) of the world food system simulated without imposing additional biofuel demand beyond the 2008 levels. Results of the reference projection were presented in the previous section. In the biofuel scenarios 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 the 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 in agricultural prices at the international and national markets; this in turn affects investment allocation and labour migration between sectors as well as reallocation of resources within agriculture.

4.4.1.1 Agricultural prices

When simulating scenarios with increased demand for food staples due to the production of first-generation biofuels, the resulting market imbalances push commodity prices upwards (Table 11). The exception is the commodity 'protein feed' where increased biofuel consumption implies lower prices compared to *REF*. This is caused by biofuel co-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 results in only very modest increases of livestock product prices.

Table 11: Impacts of biofuel scenarios on agricultural prices

	Change of price index relative to reference scenario REF (percentage)							
Scenario	*WEO-2009*		*EU-V1*		*EU-V2*		*EU-V3*	
	2020	2030	2020	2030	2020	2030	2020	2030
Crops	11	9	12	10	9	8	8	7
Cereals	12	9	13	10	11	8	10	7
Other crops	10	9	11	10	8	9	6	8
Livestock	3	0	3	0	3	0	2	0
Agricultural Production	8	7	9	7	7	6	6	5
Agricultural Exports	7	5	8	6	6	4	5	4
Wheat	13	9	15	11	11	8	9	6
Rice	6	4	6	4	5	3	5	2
Coarse grains	14	12	15	13	13	11	14	9
Bovine & Ovine	3	0	3	1	3	0	2	0
Dairy	4	1	5	2	4	1	4	1
Other meat	2	0	2	0	2	-1	2	-1
Protein feed	-21	-29	-22	-30	-21	-29	-18	-28
Other food	12	12	14	13	10	11	8	10
Non-food	-3	-1	-3	-1	-2	0	-2	0

Source: IIASA World Food System scenario simulations, June 2010.

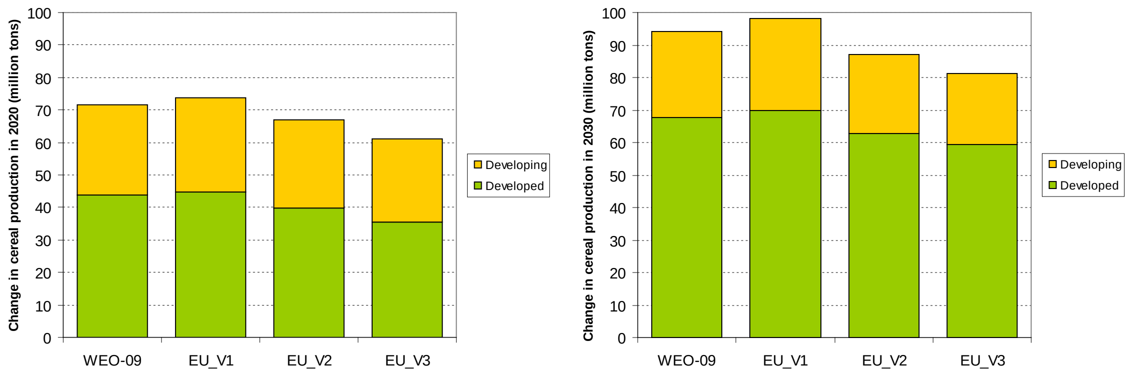
For 2020, the price increases for both cereals and other crops under the *WEO-2009* scenario are in the order of 10 percent. For biofuel demand specified in the *EU-V1* scenario (i.e. for the EU-27 about 27.1 Mtoe biofuels from crops as compared to 23.7 Mtoe in the *WEO-2009* scenario) the price impact on crops would be about 12 percent. With accelerated deployment of second-generation fuels and alternative renewable sources assumed in scenarios EU-V2 and EU-V3, the impact on cereal prices decreases to 9 and 8 percent, respectively.

4.4.1.2 Cereal demand and production

In scenario *REF* total production of cereals increased from 2.1 billion tons in 2000 to 2.7 billion tons in 2020 and nearly 3 billion tons in 2030. 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 11 shows the simulated producer response in the cereal sectors for the different biofuel scenarios in 2020 and 2030, i.e. the amount of additional cereal production realized in each scenario compared to the outcomes in scenario REF.

Figure 11: Additional cereal production in the biofuel scenarios relative to REF

a) 2020 (left panel) b) 2030 (right panel)



Source: IIASA World Food System scenario simulations, June 2010.

In 2020, the additional global use of cereal commodities for ethanol production relative to the reference simulation *REF* is around 74 million tons in *WEO-2009* and in the range of 76 million tons to 63 million tons in scenarios *EU-V1* to *EU-V3*. Production increases in response to higher agricultural prices are stronger in developed countries than in developing regions.

By 2030, the additional global use of cereals for ethanol production relative to REF is 97 million tons in WEO-2009 and ranges from 101 to 83 million tons for EU-V1 to EU-V3 with most of the additional production in developed countries.

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 70-75% of the cereals used for ethanol production are obtained from additional crop production. The remaining 25-30% comes from consumption changes of feed and food use, including feed substitution by biofuel co-products such as oilseed meals and DDGS.

4.4.1.3 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 analyzed as to what extent the additional production of crops developed on arable land as feedstocks for biofuels production will increase the value added of the agriculture sector. The percentage changes relative to the reference scenario *REF* is shown in Table 12.

Table 12: Impacts of biofuel expansion scenarios on agricultural value added

	Change in Agricultural Value Added relative to reference scenario REF (percentage)							
	WEO-2009		EU-V1		EU-V2		EU-V3	
	2020	2030	2020	2030	2020	2030	2020	2030
Developed	2.5	3.5	2.6	3.7	2.3	3.3	2.3	3.0
Developing	1.0	1.5	1.1	1.6	0.9	1.4	0.8	1.3
World	1.5	2.1	1.6	2.3	1.4	2.0	1.2	1.8

Source: IIASA World Food System scenario simulations, June 2010.

Agricultural value added increases for all biofuels scenarios at the global and regional levels. Increase rates for the world are between 1.2 and 2.3% depending on the biofuel scenario and time. There is a noticeable regional disparity with the developed world increasing their value added more than the developing countries, throughout the projection period. Thus under the assumed policy setting the agricultural sector in developed countries benefit relatively more than in developing countries in terms of percentage gains relative to scenario REF. The highest gains are projected for North America with a 6% increase in agricultural value added relative to scenario REF.

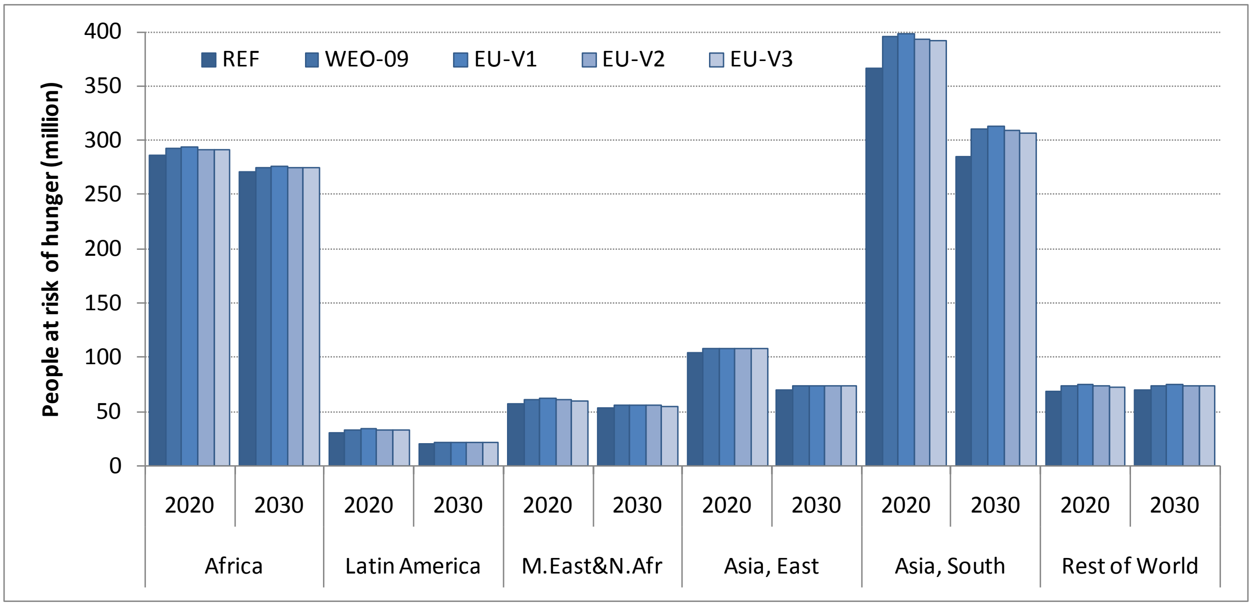
4.4.2 Sustainability implications

4.4.2.1 Impacts on the risk of hunger

To monitor the conditions of food security in different scenarios, the World Food System model calculates an indicator termed 'people at risk of hunger', based on FAO estimates of undernourished population (FAO, 2008b). According to the Reference scenario without additional biofuel expansion, the number of people at the risk of hunger declines after a peak around 2010, reaching 913 million people in 2020 and 770 million in 2030. This positive trend is intercepted by the introduction of ambitious biofuel targets. As discussed in the previous section, demand for cereals will increase in all biofuel scenarios and, despite expanding arable land to satisfy this demand, cereal prices will increase as well. Higher prices will worsen the access to and affordability of food for the poor.

Figure 12 shows that the number of people at the risk of hunger will increase relative to the REF scenario under all biofuel scenarios in all regions of the world. The increase is larger in 2020 than in 2030 because adjustments on the production side (land conversion, capacity expansion, etc.) take time, therefore achieving the 2020 biofuel targets implies diversion of food crops and increasing prices. With more time for production adjustments and for improvements in second-generation biofuel technologies, the pressure on crop prices in general and on cereal prices in particular is smaller in 2030, leading to a slower rate of decrease in the number of people at the risk of hunger relative to the reference scenario.

Figure 12 People at risk of hunger in the different scenarios



Source: IIASA World Food System scenario simulations, June 2010.

The regional distribution of the increments in the number of people at the risk of hunger relative to the reference scenario shows that South Asia and Africa will suffer most in 2020. By 2030, the increment will be lower in almost equal proportions across the world regions. The only exception is East Asia where the additional number of undernourished people will slightly increase compared to 2020. This indicates the relative scarcity of additional arable land and the lower potential for second generation biofuels in this region.

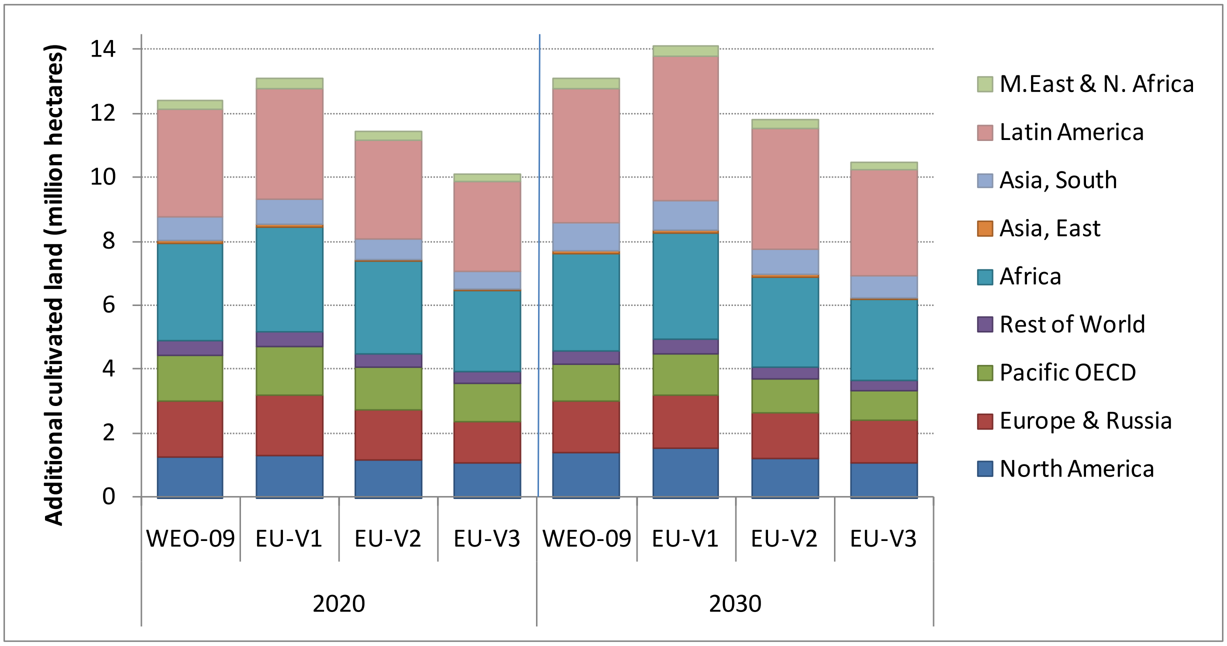
4.4.2.2 Impacts on arable land expansion

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 85 and 119 million hectares by 2020 and 2030, respectively (see Table 7). The impact of biofuel scenarios on arable land use is shown in Figure 13. For the biofuel scenario *WEO-2009* an additional 12 million hectares is put into cultivation compared to the reference projections by 2020, increasing somewhat to 13 million hectares by 2030. This represents a 10-15% increase of net arable land expansion due to biofuel use. The substantial additional land requirement during 2010-2020 is due to the assumed rapid biofuel expansion up to 2020, the very limited availability of second generation conversion technologies and the lags of impacts on agricultural productivity associated with agricultural investments triggered by higher prices.

Figure 13: Additional cultivated land use in the biofuel scenarios relative to REF



Source: IIASA World Food System scenario simulations, June 2010.

In scenarios EU-V1 to EU-V3 the respective amounts are 10-13 million hectares in 2020 and 11-14 million hectares in 2030. More than half of this additional arable land expansion is estimated to occur in Africa and Latin America.

Table 13 shows that in the biofuel expansion scenarios the ratio of additional cultivated land used per additional biofuel energy produced with first generation feedstocks and conversion technologies falls in the range of 210-225 kha/Mtoe in the shorter term, up to 2020. Over the longer term, by 2030, the estimated cultivated land required for biofuels from first generation technologies is much lower at 155-166 kha/Mtoe, due to a number of factors discussed earlier.

Table 13: Change of cultivated land per unit of additional transport energy delivered from first-generation biofuels in 2020 and 2030

	WEO-2009	EU-V1	EU-V2	EU-V3
2020				
Biofuel use relative to REF (ΔMtoe)	57.6	61.5	52.0	44.8
Cultivated land use relative to REF (Δkha)	12.4	13.1	11.4	10.1
Land use per additional energy (kha/Mtoe)	215	213	219	225
2030				
Biofuel use relative to REF (ΔMtoe)	79.7	85.0	75.4	68.3
Cultivated land use relative to REF (ΔMha)	13.1	14.1	11.8	10.5
Land use per additional energy (kha/Mtoe)	164	166	156	154

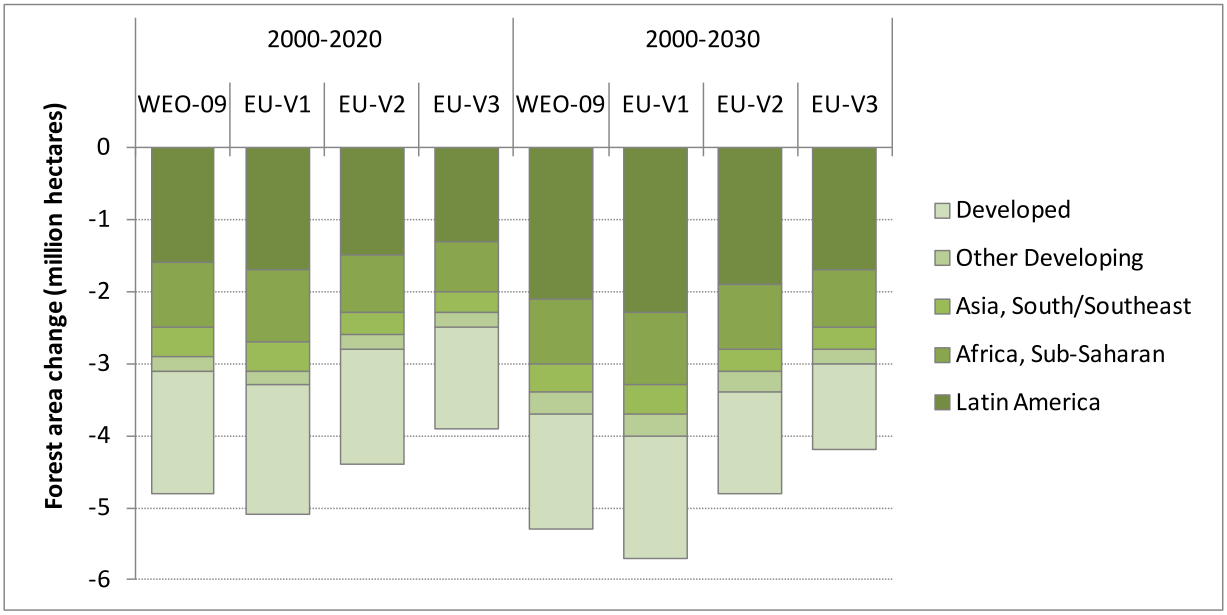
Source: IIASA World Food System scenario simulations, June 2010.

4.4.2.3 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 on the one hand, and the expansion of cultivated land as determined in the World Food System model on the other. 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 compile a consistent spatial characterization of each land grid-cell (at 5 by 5 minute longitude/latitude).

Figure 14 provides an estimation of the amount of additional deforestation directly and indirectly linked with land demand due to first-generation biofuel feedstock production.

Figure 14: Changes in forest area (relative to REF) in the biofuel scenarios by 2020 and 2030



Source: IIASA World Food System scenario simulations, June 2010.

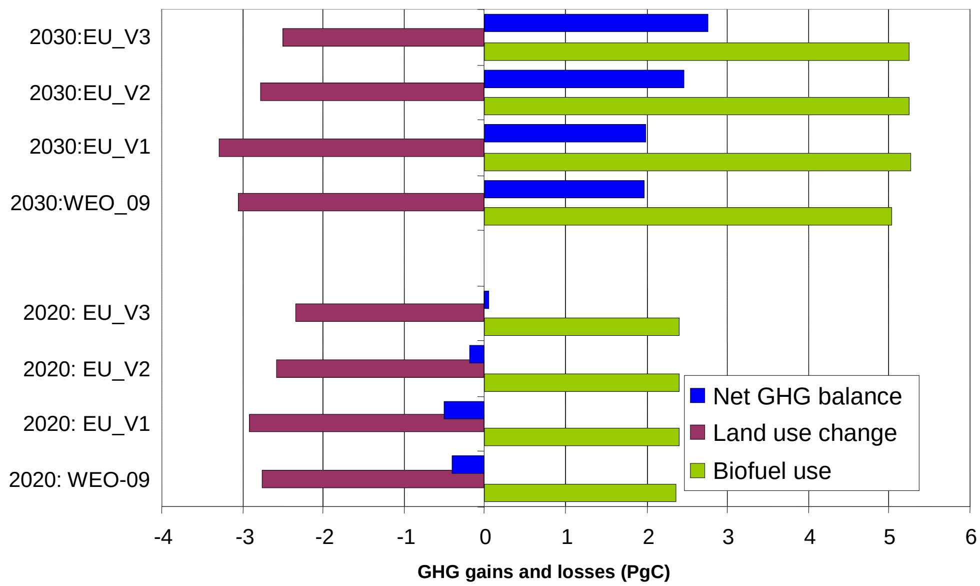
Results indicate that by 2030 biofuel feedstock production may be responsible for up to 6 million hectares of forest loss, i.e. a 10% increase in changes of forest area compared to a world without biofuel expansion. Estimates indicate the vast majority of additional deforestation occurring in Africa and Latin America. It should be noted that in the biofuel scenarios production of ligno-cellulosic feedstocks for the second-generation production chains is assumed to occur mainly on available pastures and wooded areas without causing additional deforestation.

4.4.2.4 Greenhouse gas emission saving

Since climate benefits and greenhouse gas (GHG) emission savings are the 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 established for biofuel use. 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 the 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-2009 and EU-V1 to EU-V3. The net GHG balance of a biofuel scenario (shown in blue, bar “Net GHG balance”) 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 in the biofuel scenarios



Source: IIASA World Food System scenario simulations, June 2010.

Carbon losses from vegetation and soils due to land use changes (deforestation and grassland conversion) occur mainly at the time of land conversion. By 2030, additional grassland conversion due to biofuel consumption amounts to 8 million hectares for the WEO-2009 and 6.5-8.7 million hectares for the EU-V3 to EU-V1 scenarios. In addition 5.3 million hectares (scenario WEO-2009) and 4.1-5.7 million hectares (range for scenario EU-V3 to EU-V1) of additional deforestation can be attributed to biofuel expansion.

In contrast GHG savings resulting from the replacement of fossil fuels with biofuels accumulate only gradually over time. For the biofuel scenarios net GHG balances only become positive after 2020. By 2030 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. As shown in Figure 15, the additional net greenhouse gas savings from the assumed biofuel use for the period 2020-2030 amounts to roughly 3 Pg CO2 emissions while there are hardly emissions due to additional land cover conversion resulting in a net accumulated production by 2030 of 2-3 Pg CO2 emissions.

For comparison, in 2004, the road transport sector was estimated to produce 4.7 Pg CO_2 emissions globally (IPCC, 2007).

In terms of emissions from production and land use change per unit of biofuel energy we calculate a range of 34-54 gCO_2eq/MJ for 2020 and of 21-39 gCO_2eq/MJ for 2030. The lower values refer to the global scenario with optimistic assumptions about both electricity use and second-generation biofuel availability in the EU (scenario EU-V3), the high values derive from the pessimistic scenario (scenario EU-V1).

4.5 Study scope and limitations

Given the complexity of the problem and that of the modelling system adopted for assessing it, a few caveats are in order. 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-2009 scenario applies only one overall transport fuel scenario, namely the energy reference scenario published in the World Energy Outlook 2009 (IEA, 2009):

- Today feedstocks for biofuel production are primarily derived from local production and the biofuel scenarios assume only small changes into the future. However biofuels and feedstocks may be traded more extensively in fully liberalized markets.
- The scenario analysis assesses the agronomic feasibility of biofuels scenarios but does not apply cost criteria to judge their economic viability, nor does it give specific consideration to possible alternative or additional other uses of biomass in the stationary sectors.
- 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 in EU-27 is considered via scenario variants.

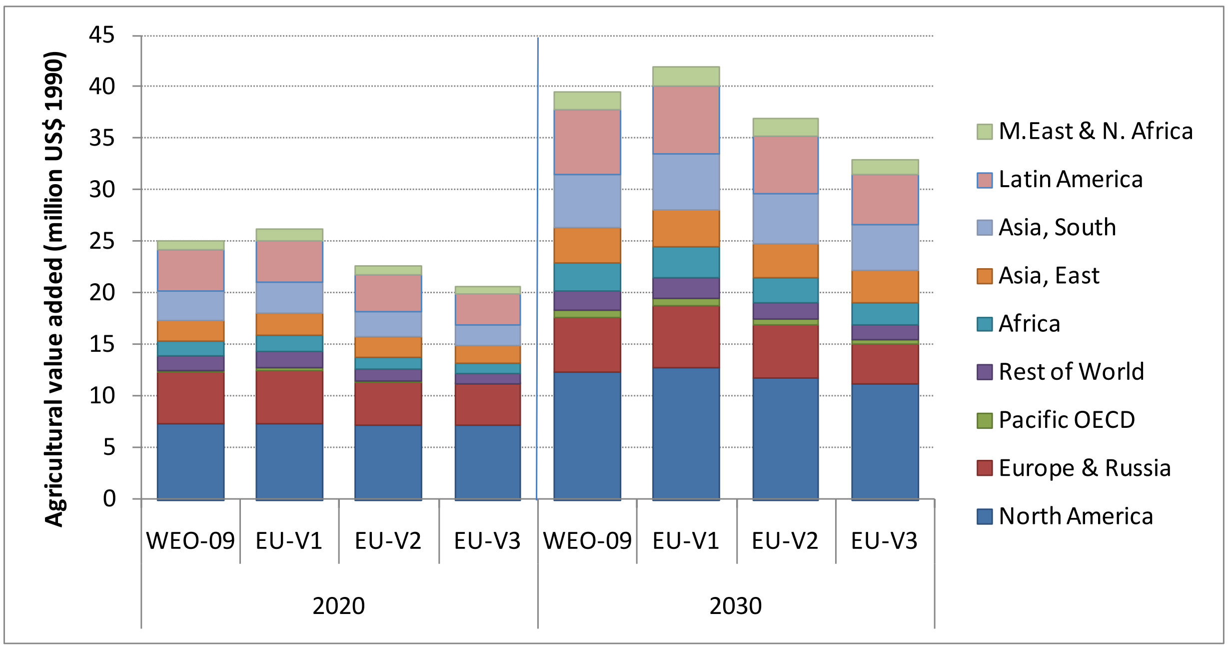
The assessments of net greenhouse gas emissions from biofuels presented in the study are subject to a considerable uncertainty range both with regards to life cycle results as well as land use change impacts.

5 Linkages between economic and sustainability targets and indicators

The biofuel scenarios analyzed in the previous section are primary driven by one key sustainability concern: to reduce the emissions of GHGs, especially CO_2, from the transport sector by increasing the share of biofuels, believed to produce less emissions per unit of energy than fossil-based transport fuels. The implementation of this target brings clear economic benefits for the sectors and regions involved in the production, processing and distribution of biofuels. This section explores the outcomes of the scenarios as measured by economic indicators (agricultural value added) and selected sustainability indicators (equity represented by the number of people at the risk of hunger), GHG emissions and deforestation (the latter also taken as a proxy for genetic diversity).

As presented in Section 4.4.1 above, agricultural value added (the GDP-equivalent for the sector) increases across a broad range of policy targets and other conditions depicted by the four biofuel scenarios relative to the REF scenario. This increase is persistent across all regions, although the agricultural sector in developed countries tends to have higher gains reflected by this indicator than developing countries (see Figure 16).

Figure 16: Changes in agricultural value added relative to the reference scenario



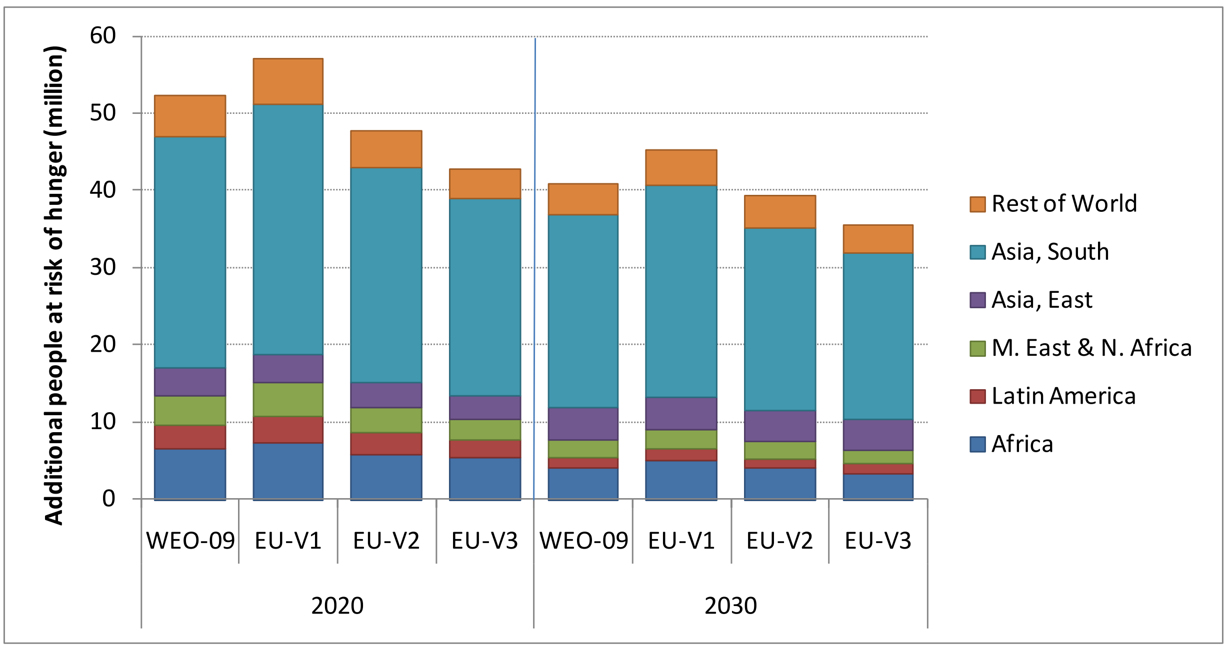
Source: IIASA World Food System scenario simulations, June 2010

The increase in agriculture value added is largely driven by the drastically increasing demand, and thus production, of cereals (more than 60 Mt in 2020 and over 80 Mt in 2030) as well as oilcrops and sugarcrops. Despite the immense increase in agricultural productivity underlying the REF scenario and the adaptation in the agriculture sector to satisfy this increased demand in the biofuel scenarios, such as expanding the arable land under cultivation and improvement in agro-technological practices (irrigation, fertilizer use, etc.), there is still an increase in agricultural prices. These price increases are significant and affect virtually all major products and commodity groups. One exception is the 'Dairy sector:' modest increases up to 5% in 2020, and negligible increases (up to 2% in 2030) across the scenarios. The second, more significant exception is the 'Other meat' commodity group: little increases of 2% in 2020, and no increase or even reduction (by about -1% in 2030) across the scenarios. This means that the agricultural sector benefits from both the quantity and price implications of the policy targets represented by the biofuel scenarios measured in terms of agricultural value added.

A widely declared and accepted criterion for sustainable development is that it has to be inclusive, delivering benefits for all people on this Earth, for present and future generations. Access to food, feed, fibre and energy at affordable prices for all is the fundamental aspects of equity.

A major equity concern is raised by the commodity price increases that affect the affordability of food and fibre for the poorest social groups, especially in developing countries. This fact is represented by changes in a social sustainability indicator, namely the indicator estimating the number of people at the risk of hunger. This indicates that about 40 to 55 million more people will face this risk in 2020 and 35 to 45 million in 2030 in the biofuel scenarios relative to the REF scenario (see Figure 17). This is a warning sign and indicates the need for countermeasures and/or balancing instruments to reduce the burden of the biofuel policies for the poor, both poor food importing countries and poor segments of populations within affected countries.

Figure 17: Additional people at risk of hunger relative to REF scenario

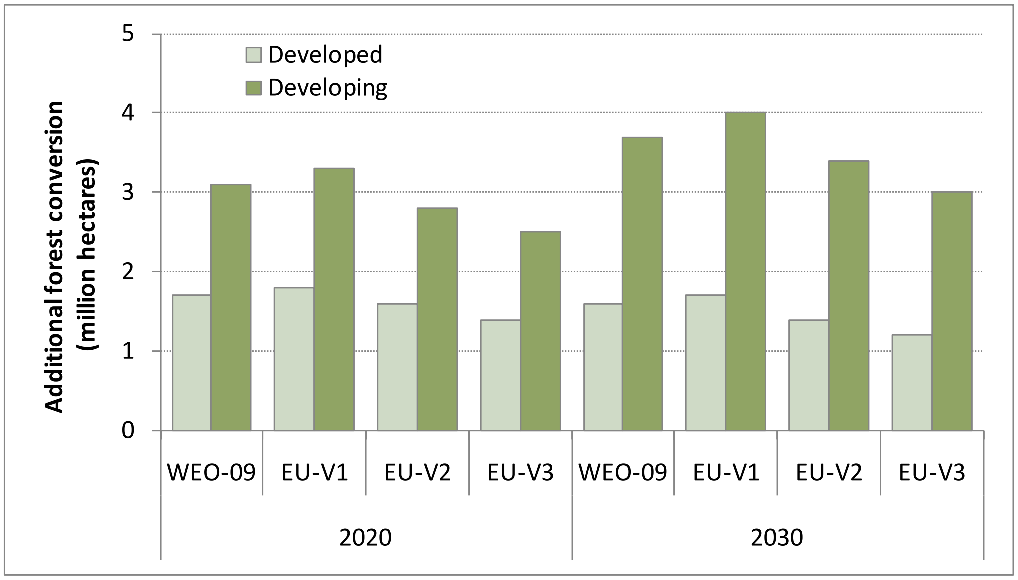


Source: IIASA World Food System scenario simulations, June 2010

The outcomes of the environmental sustainability aspects of the biofuel policies are mixed. The primary sustainability target of reducing GHG emissions from the transport sector fails in the short term: net GHG emissions (savings from biofuel use minus the increased emissions from land use change) are positive in only one of the four scenarios and negative in all other ones. The prospects are much better in the medium term: GHG emissions in 2030 are 2 to 3 PgC lower compared to the REF scenario. This indicates a clear improvement in the sustainability of the road transport system in terms of GHG emissions.

Yet the sustainability improvements in terms of GHG emissions come at a price of degrading sustainability in another dimension. Driven by the increasing demand for arable land due to the area required for biofuel production, substantial increase in the rate of deforestation is projected to take place in all major world regions in all scenarios relative to REF (see Figure 18). Corresponding to the distribution of forested areas across the world, the share in the additionally deforested global area is significantly higher in developing than in developed countries.

Figure 18: Forest area losses (relative to REF) under the biofuel scenarios by 2020 and 2030



Source: IIASA World Food System scenario simulations, June 2010.

The largest amount of deforested area is projected for Latin America but the extent of deforestation is also significant in Sub-Saharan Africa. Although it is difficult to quantify the linkages between deforestation and the threat to genetic diversity, it is widely believed that tropical forests harbour an enormous share of the Earth's genetic pool. Hence increased deforestation also poses a considerable threat for genetic diversity.

Across all these economic and sustainability indicators, the asymmetrical distribution between developed and developing regions raises severe equity concerns. The bulk of the economic benefits (measured by agricultural value added) accrue to developed countries. In contrast the social burden falls on developing countries as reflected by the increasing number of people at the risk of hunger in most regions. A similar bias can be observed in the environmental dimension: additional deforestation triggered by the biofuel targets will mostly affect developing regions.

This leads to the conclusion that economic and sustainability characteristics of the global agricultural system are resulting from a complex set of cause-effect relationships. It requires an in-depth representation of the natural resource base (land, climate, agronomic features) and the socio-economic processes involved in their utilization. Policies and decision making range from international agreements (climate, trade, subsidies like CAP) to national policies (e.g., CAP, biofuel mandates) down to decisions at the farm level. This globally connected system involves remote causations in which policies pursued in one region or country affect the conditions (commodity trade and prices) in other regions. The two main implications are that sustainability targets in one region can negatively affect prospects for sustainable development in other regions, and that sustainability improvements in one domain can degrade the sustainability characteristics in another domain. Analysts need to assess these linkages thoroughly so that policymakers can make informed judgements about the benefits and costs of the policy options available to them.

References

EC (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, European Commission, Brussels.

FAO (2006), World Agriculture: towards 2030/2050, Interim Report, http://www.fao.org/es/esd/gstudies.htm

FAO (2008a). The State of Food and Agriculture. Biofuels: prospects, risks and opportunities. Food and Agriculture Organization of the United Nations, Rome.

FAO (2008b). The State of Food Insecurity in the World, 2008. Food and Agriculture Organization of the United Nations, Rome.

FAO (2009) J. Bruinsma, May 2009; personal communication).

FAO (2010), Global Forest Resources Assessment 2010, Food and Agriculture Organization of the United Nations, Rome.

Fischer G., K. Frohberg, M.A. Keyzer, K.S. Parikh (1988). Linked National Models: a Tool for International Policy Analysis, Kluwer Academic Publishers, 214pp.

Fischer, G., K. Frohberg, M.L. Parry, C. and Rosenzweig (1994). Climate Change and World Food Supply, Demand and Trade: Who Benefits, Who Loses? *Global Environmental Change* 4(1), 7–23.

Fischer G., H. van Velthuizen, M. Shah, F.O. Nachtergaele (2002a). Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results. IIASA RR-02-02, IIASA, Laxenburg, Austria.

Fischer, G., M. Shah and H. van Velthuizen (2002b). *Climate Change and Agricultural Vulnerability*. Special Report as contribution to the World Summit on Sustainable Development, Johannesburg 2002. International Institute for Applied Systems Analysis, Laxenburg, Austria. pp 152.

Fischer, G., M. Shah, F.N. Tubiello, H van Velhuizen (2005). *Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080*. Phil. Trans. Royal Soc. B, doi:10.1098/rstb.2005.1744.

Fischer, G., F. Nachtergaele, S. Prieler, E.Teixeira, H.T. van Velthuizen, L. Verelst, D. Wiberg, (2008). *Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008)*. IIASA, Laxenburg, Austria and FAO, Rome, Italy.

Fischer G, Hizsnyik E, Prieler S, Shah M, Velthuizen H van (2009). Biofuels and Food Security. OFID/IIASA, Vienna/Laxenburg. <Available at: http://www.iiasa.ac.at/Research/LUC/luc07/Homepage-News-Highlights/Biofuels%20Report%20Final.pdf>

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

IEA (International Energy Agency) (2009). *World Energy Outlook 2009*. OECD/IEA. Paris. 691 p.

IIASA/FAO, 2010. Global Agro-ecological Zones (GAEZ v3.0). International Institute for Applied Systems Analysis, Laxenburg, Austria and Food and Agriculture Organization of the United Nations, Rome, Italy.

IPCC (2000), Special Report on Emissions Scenarios, Nakicenovic N., R. Swart (eds.), A Special Report of IPCC Working Group III, Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC (2006). IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. Volume 4, IGES: Japan.

IPCC (2007) Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

OECD (2008), Biofuel Support Policies: An Economic Assessment, Organisation for Economic Co-operation and Development, Paris.

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

Rosenzweig, C. and Parry, M.L. (1994), Impacts of Climate Change on World Food Supply, Nature 367, 133–138.

Tubiello, F., G. Fischer (2007), Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000–2080. Technological Forecasting & Social Change 74, 1030-1056.

UN (2009). World Population Prospects: The 2008 Revision. United Nations, March 2009.