Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# Global land-use implications of first and second generation biofuel targets

Petr Havlík [a,]*, Uwe A. Schneider [b], Erwin Schmid [c], Hannes Böttcher [a], Steffen Fritz [a], Rastislav Skalský [d], Kentaro Aoki [a], Stéphane De Cara [e], Georg Kindermann [a], Florian Kraxner [a], Sylvain Leduc [a], Ian McCallum [a], Aline Mosnier [a], Timm Sauer [b], Michael Obersteiner [a]

[a] International Institute for Applied Systems Analysis (IIASA), Forestry Program, Schlossplatz 1, A-2361 Laxenburg, Austria
[b] University of Hamburg, Centre for Marine and Atmospheric Sciences, Sustainability and Global Change (FNU), Germany
[c] University of Natural Resources and Applied Life Sciences, Vienna (BOKU), Institute of Sustainable Economic Development, Austria
[d] Soil Science and Conservation Research Institute, Bratislava, Slovakia
[e] INRA, UMR 210 Economie Publique INRA-AgroParisTech, Thiverval-Grignon, France

ARTICLE INFO

*Article history:*
Received 14 March 2009
Accepted 11 March 2010

*Keywords:*
Biofuels
Land use change
Modelling

ABSTRACT

Recently, an active debate has emerged around greenhouse gas emissions due to indirect land use change (iLUC) of expanding agricultural areas dedicated to biofuel production. In this paper we provide a detailed analysis of the iLUC effect, and further address the issues of deforestation, irrigation water use, and crop price increases due to expanding biofuel acreage. We use GLOBIOM – an economic partial equilibrium model of the global forest, agriculture, and biomass sectors with a bottom-up representation of agricultural and forestry management practices. The results indicate that second generation biofuel production fed by wood from sustainably managed existing forests would lead to a negative iLUC factor, meaning that overall emissions are 27% lower compared to the "No biofuel" scenario by 2030. The iLUC factor of first generation biofuels global expansion is generally positive, requiring some 25 years to be paid back by the GHG savings from the substitution of biofuels for conventional fuels. Second generation biofuels perform better also with respect to the other investigated criteria; on the condition that they are not sourced from dedicated plantations directly competing for agricultural land. If so, then efficient first generation systems are preferable. Since no clear technology champion for all situations exists, we would recommend targeting policy instruments directly at the positive and negative effects of biofuel production rather than at the production itself.


## 1. Introduction

Many countries have set up bioenergy policies to support and regulate the production and use of fuels from biomass feedstocks (e.g. US, EU, Brazil, China, and India). The principal justification for these policies is to decrease the dependency on fossil fuels, especially in oil importing countries. Increasing biofuel use may also help to decrease greenhouse gas emissions because the carbon that is emitted during their combustion was recently extracted from the atmosphere by growing plants (Farrell et al., 2006; Kim and Dale, 2006). In many countries, biofuels are expected to positively affect rural development and the vitality of agricultural operations. This holds true particularly in countries where agriculture currently receives high governmental subsidies. Additionally, one should note that biofuel additives to gasoline were initially pursued as a means to reduce air pollution from leaded gasoline (Nadim et al., 2000).

Three different types of biofuels currently play a major role at the global level, all belonging to the so-called "first generation" fuels: ethanol, fatty acid methyl ester (FAME or biodiesel), and pure plant oil (PPO). All have reached a considerable state of the art in production and are commercially available (Bringezu et al., 2007). Most of the worldwide biofuel production is ethanol, which is mainly produced in the USA and Brazil from either corn or sugarcane. In Europe, potato, wheat or sugar beet is the common feedstock for ethanol. However, ethanol plays only a minor role in European biofuel production, with the large majority coming from biodiesel. About 70% of biodiesel is in Europe produced from rapeseed oil, the rest then from soybean oil (17%), and to an even smaller extent from sunflower and palm oil (USDA FAS, 2008). These biofuels have been subject to numerous life cycle assessments focusing on energy and greenhouse gas emission balances (for a review see e.g. OECD, 2008). Although the ranges of the GHG savings estimates are large, they tend to be positive for all the principal first generation biofuels, like sugarcane ethanol, rapeseed biodiesel or palm oil biodiesel, with the exception of corn and wheat ethanol where several studies also show potentially small negative effects. These assessments

* Corresponding author. Tel.: +43 2236 807 511; fax: +43 2236 807 599.
*E-mail address:* havlik.petr@gmail.com (P. Havlík).

0301-4215/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2010.03.030

however did not include emissions caused by land use changes. Recent studies show that local GHG emission offsets from these fuels may be compromised by increasing emissions elsewhere due to intensification and deforestation (Fargione et al., 2008; Searchinger et al., 2008).

Second generation biofuels, represented for example by ethanol and methanol produced from woody biomass, are more energy efficient and more flexible regarding their feedstock. The possibility to use cellulosic and heterogeneous biomass suggests lower costs and a better environmental performance (e.g. Granda et al., 2007; Hill, 2007). Although second generation biofuel technology is still in a developmental stage and not available on a commercial basis (Kaltschmitt, 2001), promising research advances and demonstration projects (see Hamelinck and Faaij, 2006; Hamelinck et al., 2005) have already triggered ambitious future policy targets regarding their role within the overall energy portfolio – along with funding for further research and development (e.g. US Energy Independence and Security Act of 2007, USDOE, 2008). Feedstock for second generation can be a by- or co-product or even waste (Cantrell et al., 2008; Sklar, 2008), or be supplied by dedicated plantations. The latter ones can be established on marginal lands (Tilman et al., 2006; Zomer et al., 2008), or enter into direct competition with conventional agricultural production (Field et al., 2008; Gurgel et al., 2007) and other services.

Biofuels are hotly debated today because their overall impacts, also with respect to wider ecological and socio-economic issues, are uncertain and difficult to assess (Upham et al., 2009). Difficulties arise since direct biofuel benefits are linked to indirect land use impacts and may lead to adverse externalities regarding GHG emission balances, ecosystem services, and security of food and water (Koh and Ghazoul, 2008). Therefore, a proper assessment of biofuel impacts has to integrate many different scales. On the one hand, a global representation of agricultural and forest commodity markets is needed because these commodities are traded internationally and trade is the fundamental driver of indirect land use changes. On the other hand, biofuel assessments need a relatively high spatial and technical disaggregation to adequately account for heterogeneous land qualities, technological differences, and possible adaptations. For the overall environmental performance, it makes a great difference whether biofuels lead for instance to the replacement of tropical rainforests in Brazil or to the restoration of degraded farm lands in India.

Existing assessments of biofuels can be grouped regarding their spatial, technological, and impact scope and their underlying assessment methods. Natural science, engineering based, and geographic studies often compute technical potentials (Smeets et al., 2007). While market adjustments are usually neglected, technological choices and land use impacts are exogenously dictated. Depending on data availability, the employed methods are well suited to portray the heterogeneity of land and existing technologies. Economic studies compute economic potentials of biofuels (Schneider and McCarl, 2003) and range from farm level to global general equilibrium assessments. Farm level models are generally limited to specific regions and use constant resource rents and commodity prices (Bennett and Anex, 2008). Market adjustments and indirect land use effects are not adequately included. At the other extreme, global general equilibrium models (Yang et al., 2008) use a top-down macroeconomic approach that integrates market adjustments. However, their account of indirect land use impacts and associated externalities is very coarse at best.

The diverse strengths and weaknesses of disciplinary studies and individual models imply that credible answers to the full impacts of biofuels might only be obtained through integrated global assessments. Such assessments should link engineering, geographic, and economic tools and address different land qualities, management adaptations, and global market feedbacks. In this paper, we take a step towards a comprehensive impact assessment of biofuels. Particularly, we use detailed geographic data to represent the natural variation in land quality at the global level. We employ complex biophysical process models to simulate, inter alia, possible agricultural management adaptations and their impacts on yields, GHG emissions, and water requirements under different land qualities. Explicit technological data for agricultural and forest management alternatives as well as first and second generation biofuel processes are simultaneously integrated in a bottom-up, partial equilibrium model of the global agricultural and forest sectors, GLOBIOM. This model is used here to assess different global biofuel scenarios regarding their market feedbacks and their indirect land use impacts and associated environmental consequences worldwide. The scenarios cover both first and second generation production technologies, and investigate several different settings with respect to the feedstock sourcing, hence covering a large part of the spectrum of current and future biofuel options.

The rest of the paper is structured as follows: in the next section we provide a description of the methodology applied, starting by briefly presenting the general aspects of the applied model and the unifying data infrastructure. Then we present the individual model components in detail, and close that section by providing information about our assessment of the global potentials for short rotation plantation bioenergy feedstock. Section 3 contains our numerical simulations, where we first define the baseline assumptions and the investigated scenarios, and then present the obtained results. The most important results are then summarized and put into perspective through discussion in Section 4. Section 5 concludes this paper.

## 2. Methods and data

### 2.1. *Description of GLOBIOM*[1]

The Global Biomass Optimization Model (GLOBIOM) is a global recursive dynamic partial equilibrium model integrating the agricultural, bioenergy and forestry sectors with the aim to provide policy analysis on global issues concerning land use competition between the major land-based production sectors. The general concept and structure of GLOBIOM is similar to the US Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model (Schneider et al., 2007). The global agricultural and forest market equilibrium is computed by choosing land use and processing activities to maximize the sum of producer and consumer surplus (Eq. (1) in Appendix A) subject to resource, technological, and policy constraints, as described by McCarl and Spreen (1980). Prices and international trade flows are endogenously determined for respective aggregated world regions. The flexible model structure enables one to easily change the model resolution; currently two global region definitions are being simultaneously used, either 11 regions corresponding to the regions definition by the Greenhouse Gas Initiative (GGI) at the International Institute for Applied Systems Analysis (IIASA) (GGI Scenario Database, 2007), or 27 regions, representing a disaggregation of the 11 regions adapted to enable linkage with the POLES (Prospective Outlook on Long-Term Energy Systems) model (Criqui et al., 1999).

[1] Readers interested in details going beyond the scope of this paper, are invited to contact directly the authors and to visit www.globiom.org.

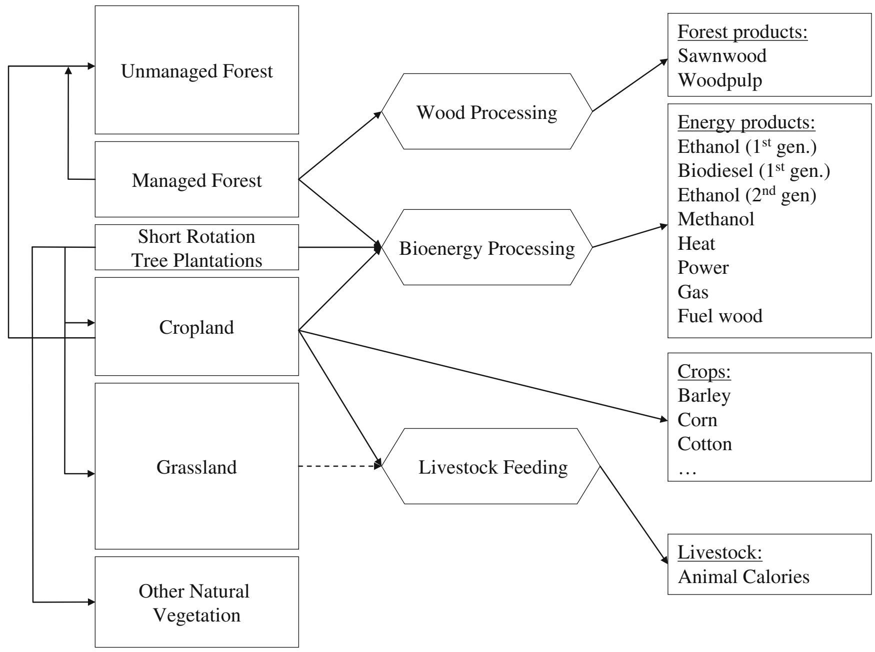


**Fig. 1.** GLOBIOM land use and product structure.

The market is represented by implicit product supply functions based on detailed, geographically explicit, Leontief production functions, and explicit, mostly constant elasticity, product demand functions. Each individual production technology is specified as Leontief function, i.e. a function which implies fixed input – output ratios. Because each primary product can be produced with different production technologies, discrete changes in input – output ratios are possible by selecting a different mix of production technologies. Explicit resource supply functions are used only for water supply. In what follows we will present the model along Fig. 1 where the product chains and the land use change options are represented. But before we start the detailed model description, we briefly present the concept of homogeneous response units around which the majority of input parameters, as well as the model itself, are structured.

### 2.2. Data concept and processing

Land resources and their characteristics are the fundamental elements of our modelling approach. In order to enable global bio-physical process modelling of agricultural and forest production, a comprehensive database has been built (Skalský et al., 2008), which contains geo-spatial data on soil, climate/weather, topography, land cover/use, and crop management (e.g. fertilization, irrigation). The data were compiled from various sources (FAO, ISRIC, USGS, NASA, CRU UEA, JRC, IFRPI, IFA, WISE, etc.) and significantly vary with respect to spatial, temporal, and attribute resolutions, thematic relevance, accuracy, and reliability. Therefore, data were harmonized into several common spatial resolution layers including 5 and 30 arcmin as well as country layers. Subsequently, Homogeneous Response Units (HRU) have been delineated by geographically clustering according to only those parameters of the landscape, which are generally not changing over time and are thus invariant with respect to land use and management or climate change. At the global scale, we have included five altitude classes, seven slope classes, and five soil classes. In a second step, the HRU layer is intersected with a $0.5^\circ \times 0.5^\circ$ grid and country boundaries to delineate Simulation Units (SimU) which contain other relevant information such as global climate data, land category/use data, irrigation data, etc. For each SimU a number of land management options are simulated using the bio-physical process model EPIC (Environmental Policy Integrated Climate Model; Izaurralde et al., 2006; Williams, 1995). And the SimUs are the basis for estimation of land use/management parameters in all other supporting models as well.

The HRU concept assures consistent aggregation of geo-spatially explicit bio-physical impacts in the economic land use assessment. In GLOBIOM, we can choose at which level of resolution the model is run, and aggregate the inputs consistently. As shown in Appendix A, each land related activity and all land resources are currently indexed by country, altitude, slope, and soil class. The information relevant to the $0.5^\circ \times 0.5^\circ$ grid layer has been averaged to keep the model size and computational time within reasonable limits.

### 2.3. Model structure

The model directly represents production from three major land cover types: cropland, managed forest, and areas suitable for short rotation tree plantations.[2] Crop production accounts for more than 30 of the globally most important crops. The average yield level for each crop in each country is taken from FAOSTAT. Management related yield coefficients according to fertilizer and irrigation rates are explicitly simulated with EPIC for 17 crops (barley, dry beans, cassava, chickpea, corn, cotton, ground nuts, millet, potatoes, rapeseed, rice, soybeans, sorghum, sugarcane, sunflower, sweet potatoes, and wheat). These 17 crops together represent nearly 80% of the 2007 harvested area as reported by FAO. Four management systems are considered (irrigated, high input – rainfed, low input – rainfed and subsistence management systems) corresponding to the International Food and Policy Research Institute (IFPRI) crop distribution data classification

[2] Grassland production is so far represented only indirectly, through increased cost of land use change, without explicit link to the livestock feed requirements. Work is going on to improve this aspect in the next version of the model.

Please cite this article as: Havlík, P., et al., Global land-use implications of first and second generation biofuel targets. Energy Policy (2010), doi:10.1016/j.enpol.2010.03.030

(You and Wood, 2006). Only two management systems are differentiated for the remaining crops (bananas, other dry beans, coconuts, coffee, lentils, mustard seed, olives, oil palm, plantains, peas, other pulses, sesame seed, sugar beet, and yams) – rainfed and irrigated. Rainfed and irrigated crop yield coefficients, and crop specific irrigation water requirements for crops not simulated with EPIC, and costs for four irrigation systems for all crops, are derived from a variety of sources as described in Sauer et al. (2010). The linkage between primary (crop) production and the land resources is represented in Eq. (4) of Appendix A. The irrigation water balance is represented by accounting Eq. (9) and in the objective function, Eq. (1). Thus, water scarcity is expressed through the parameterization of the water supply function.

Crop supply can enter one of three processing/demand channels: consumption, livestock production, and biofuel production (Fig. 1). Demand is modelled by constant elasticity functions parameterized using FAOSTAT data on prices and quantities, and own price elasticities as reported by Seale et al. (2003). An aggregated regional livestock production representation is used, where a bundle of livestock products (bovine meat, chicken meat, equine meat, pig meat, sheep and goat meat, turkey meat, milk, and eggs) is aggregated to a generic commodity – "animal calories". The feed crops requirements have been calculated from the Supply Utilisation Accounts, FAOSTAT, and constitute the link between livestock production and cropland. Demand for livestock products is represented through downward sloping demand curves. Biofuel options from crops include first generation technologies for (a) ethanol from sugarcane and corn and (b) biodiesel from rapeseed and soybeans. The processing data, conversion coefficients and cost, are based on Hermann and Patel (2007) for ethanol, and on Haas et al. (2006) for biodiesel. Market demand for ethanol and biodiesel is represented through vertical demand functions (Eq. (2) in Appendix A), the supply – demand balance according to Eq. (3).

Primary forest production from traditional managed forests is characterized also at the level of SimUs. The most important parameters for the model are mean annual increment, maximum share of saw logs in the mean annual increment, and harvesting cost. These parameters are shared with the G4M model – a successor of the model described by Kindermann et al. (2006). More specifically, mean annual increment for the current management, is obtained by downscaling biomass stock data from the Global Forest Resources Assessment (FAO, 2006a) from the country level to a $0.5^\circ \times 0.5^\circ$ grid using the method described in Kindermann et al. (2008). The downscaled biomass stock data are subsequently used to parameterize increment curves. Finally, the saw logs share is estimated by the tree size, which in turn depends on yield and rotation time. Harvesting costs are adjusted for slope and tree size as well.

Five primary forest products are defined: saw logs, pulp logs, other industrial logs, traditional fuel wood, and biomass for energy. Saw logs, pulp logs and biomass for energy are further processed. Sawn wood and wood pulp production and demand parameters rely on the 4DSM model described in Rametsteiner et al. (2007). FAO data and other secondary sources have been used for quantities and prices of sawn wood and wood pulp. For processing cost estimates of these products an internal IIASA database and purchased data (e.g. RISI database for locations of individual pulp and paper mills, with additional economic and technical information, http://www.risiinfo.com) were used. Biomass for energy can be converted in several processes: combined heat and power production, fermentation for ethanol, heat, power and gas production, and gasification for methanol and heat production. Processing cost and conversion coefficients are obtained from various sources (Biomass Technology Group, 2005; Hamelinck and Faaij, 2001; Leduc et al., 2008; Sørensen, 2005). Demand for woody bioenergy production is implemented through minimum quantity constraints, similar to demand for other industrial logs and for firewood, shown in Appendix A (see Eq. (2)).

Woody biomass for bioenergy can also be produced on short rotation tree plantations. To parameterize this land use type in terms of yields, we carried out our own evaluation of the land availability and suitability, described in detail in the next subsection. Calculated plantation costs involve the establishment cost and the harvesting cost. The establishment related capital cost includes only sapling cost for manual planting (Carpentieri et al., 1993; Herzogbaum GmbH, 2008). Labour requirements for plantation establishment are based on Jurvélius (1997), and consider land preparation, saplings transport, planting and fertilization. These labour requirements are adjusted for temperate and boreal regions to take into account the different site conditions. The average wages for planting are obtained from ILO (2007).

Harvesting cost includes logging and timber extraction. The unit cost of harvesting equipment and labour is derived from various datasets for Europe and North America (e.g. FPP, 1999; Jiroušek et al., 2007; Stokes et al., 1986; Wang et al., 2004). Because the productivity of harvesting equipment depends on terrain conditions, a slope factor (Hartsough et al., 2001) was integrated to estimate total harvesting cost. The labour cost, as well as the cost of saplings, is regionally adjusted by the ratio of mean PPP (purchasing power parity over GDP) (Heston et al., 2006).

As represented graphically in Fig. 1, and analytically in Eqs. (5)–(8) in Appendix A, we allow for endogenous change in the land cover/use within the available land resources. Expansion into land cover/use types not covered in the model is not allowed, and thus the total land area remains fixed over the whole simulation horizon. When carrying out simulations over several periods, changes made in one period, are consistently transferred into the next period, introducing recursive dynamics into the model. Land use change options are on the one hand limited through general restrictions on conversion from one land use to another; e.g. cropland expansion into other natural vegetation is not allowed anywhere.[3] On the other hand, land suitability criteria linked to production potentials exclude selectively land use conversion to a particular land use type in a particular SimU. Land use suitability is taken into account either indirectly through estimated crop and forest productivity, or directly by not only calculating the production potentials but also by explicitly delineating suitable areas. This detailed direct suitability analysis has been carried out for short rotation tree plantations and is presented below.

As expressed by Eq. (10) (see Appendix A) and by the objective function, GLOBIOM allows for accounting, and eventually taxing, of the major greenhouse gas emissions/sinks related to agriculture and forestry. The calculation of emission coefficients depends on the emission source. $N_2O$ emissions from application of synthetic fertilizers are calculated according to the IPCC Guidelines (IPCC, 1996), on the basis of fertilizer use as simulated in EPIC, or for crops which are not yet simulated, using fertilizer application rates derived from IFA (1992) and FAOSTAT. Coefficients for CH4 emissions from rice production, and from enteric fermentation and manure management, are derived from EPA (2006) by recalculating the total values per activity level.

[3] This approach enables a quick assessment of the role of currently uncertain parameters like the actual cost of land cover conversion, through scenario analysis. In this sense, restriction means a prohibitively high cost, e.g. because the land considered as free is already (in)formally used for some other activities.

**Table 1**
Lifecycle GHG savings from substitution of fuels by biofuels, without land use change related emissions.

| Biofuel | Feedstock | GHG saving (g $CO_2$ eq. $MJ^{-1}$) |
|---|---|---|
| Ethanol[a] | Corn | 35.58 |
| Ethanol[a] | Sugarcane | 59.99 |
| Biodiesel[a] | Rapeseed | 41.18 |
| Biodiesel[a] | Soybeans | 38.79 |
| Ethanol[b] | Woody biomass | 63.10 |
| Methanol[b] | Woody biomass | 77.60 |

[a] Calculations based on Renewable Fuels Agency (2009).
[b] Calculations based on CONCAWE/JRC/EUCAR (2007).

In this paper, we focus on two greenhouse gas account items: (i) lifecycle GHG savings from substitution of fossil fuels by biofuels and (ii) GHG savings/emissions from land use change. $CO_2$ coefficients for the various bioenergy paths are calculated using parameters from CONCAWE/JRC/EUCAR (2007) and Renewable Fuels Agency (2009), Table 1. Greenhouse gas accounts of land use change activities are based on the carbon content in *above- and below-ground living biomass* of the different land cover classes in equilibrium state. Carbon content for forests is taken from Kindermann et al. (2008). Carbon content in the biomass of short rotation plantations is calculated based on our own estimates of their productivity. Finally, for parameterization of carbon in grasslands and in other natural vegetation, we use the biomass map by Ruesch and Gibbs (2008). The living biomass carbon content in cropland is neglected, because it is relatively small and diverse, and no sufficient data is available. $CO_2$ coefficients for emissions and sinks due to land use change are calculated as the difference in carbon content between the initial and the new land cover classes.

The final model calibration, supposed to correct data imperfections and get the baseline solution close to the observed values, was performed by adjusting the cost parameters of selected activities so that for the baseline activity levels, their marginal costs equal marginal benefits, as assumed by microeconomic theory. The controlled activities are SimU specific crop areas, and regional primary forest products supply and animal calorie supply.

The model is written and solved in GAMS IDE.

### 2.4. Analysis of the land reserve

The estimation of area potentials for biomass plantations followed an approach proposed by Zomer et al. (2008). It included thresholds of tree growth based on aridity, temperature, elevation, population density, and existing land cover. The Aridity Index developed by Zomer et al. (2008) uses the ratio between mean annual precipitation and mean annual evapotranspiration. We obtained the derived aridity map directly from the authors of the study. The temperature limitation threshold was modified and data with a higher temporal resolution was included. Calculation of the temperature threshold was based on data provided by the European Centre for Medium Range Weather Forecasting (ECMWF) that can be downloaded from the JRC MARS FOOD archive (see http://mars.jrc.it/marsfood/ecmwf.htm). The original average temperature of 10 day periods was averaged over the growing season. Growing season was defined as time of the year where average temperature is equal or larger than 5 °C. By iteration we defined a threshold value of 10 °C average temperature in growing season that matched with the observed northern tree line in GLC-2000 in North America and most parts of Siberia.

High elevation areas with elevation of more than 3500 m were excluded from potential plantation area. These were based on a Digital Elevation Map of 1 km (based on SRTM 90 m Digital Elevation Data available at http://srtm.csi.cgiar.org). In addition, population densities of above 1000 people/km$^2$ were excluded from plantation potential; mostly areas in China and India but also the island of Java fall into this category. However, it depends very much on the form of settlements; even lower population densities could make the establishment of large scale plantations very unlikely. The population map was based on gridded population data from CIESIN (2005).

**Table 2**
Land suitable for afforestation in different GLC 2000 Land Cover Classes.

| Category | GLC classes | Afforestation potential (Mha) |
|---|---|---|
| Forest | All forest categories of GLC-2000 including the mosaic forest/natural vegetation | 3151 |
| Agriculture/ cropland | All managed and cultivated areas including mosaics cultivated managed/natural vegetation, cultivated managed/forest cover | 1171 |
| Grassland | Herbaceous cover | 299 |
| Other natural vegetation | Shrubland and sparse shrubs/sparse grass | 510 |

The land that remained unaffected by the constraints mentioned above was classified into four categories derived from GLC 2000 Land Cover Classes (Table 2).

The land suitable for afforestation in the four land cover classes as well as the average net primary productivity (NPP) values is extracted per SimU. The NPP values were based on potential NPP from Cramer et al. (1999). The NPP, truncated for the highest values corresponding to 5% of area in each region, was then used to scale the maximum mean annual increments derived from FAO and other various databases (e.g. Alig et al., 2000; Chiba and Nagata, 1987; FAO, 2006b; Mitchell, 2000; Stanturf et al., 2002; Uri et al., 2002; Wadsworth, 1997; Webb et al., 1984) proportionally for each SimU, providing finally the SimU specific potentials. Fig. 2 shows these potentials for land cover classes considered for plantations in the following, Model application, section – agriculture/cropland, grassland, and other natural vegetation.

## 3. Model application

### 3.1. Baseline assumptions

As GLOBIOM operates in partial equilibrium, several parameters enter the 2030 projections as exogenous drivers. Wood and food demand is driven by gross domestic product (GDP) and population changes. In addition, food demand must meet minimum per capita calorie intake criteria, which are differentiated with respect to the source between crop and livestock calories. Demand is calculated for the different regions on the basis of projections presented in FAO (2006a). The regional population development is taken from the B2 scenario of the Special Report on Emissions Scenarios (SRES) as provided by the GGI Scenario Database (2007). On the supply side, we make a conservative assumption of zero "autonomous" technological progress in crop improvement, which would otherwise exogenously shift the supply curve either upwards or downwards. However, as we represent several crop management systems and allow for endogenous switches between rainfed and irrigated agriculture, the average yield is still sensitive to the market signals.

The global bioenergy baseline is defined according to POLES simulation results corresponding to an updated version of Russ

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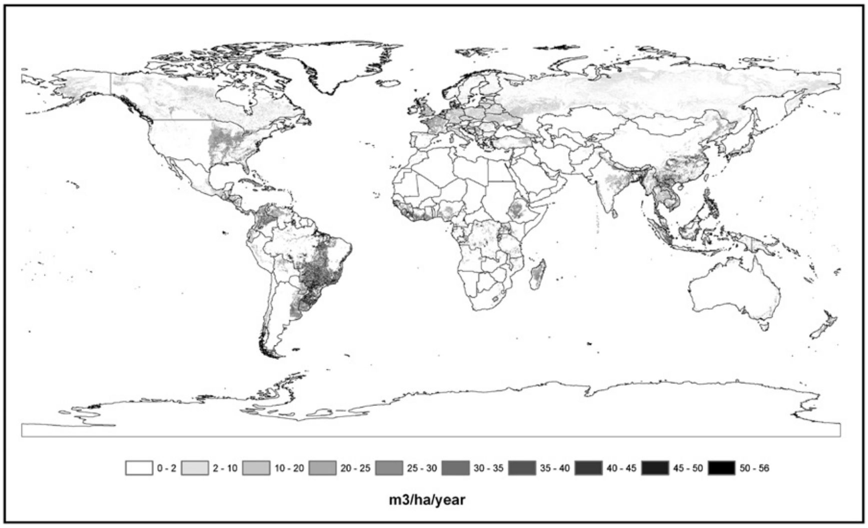


**Fig. 2.** Estimated potential productivity (mean annual increment) of short rotation tree plantations on agriculture/cropland, grassland and other natural vegetation.

**Table 3**
Baseline global bioenergy production as estimated by POLES.

| Energy carrier | Units | 2000 | 2010 | 2020 | 2030 |
|---|---|---|---|---|---|
| Heat and power | Mtoe of dry biomass | 51 | 107 | 266 | 447 |
| Direct biomass use | Mtoe of dry biomass | 950 | 1019 | 1125 | 1201 |
| Liquid fuels – first generation | Mtoe of fuel | 10 | 101 | 140 | 165 |
| Liquid fuels – second generation | Mtoe of fuel | 0 | 3 | 13 | 112 |

**Table 4**
Scenarios considered in the analysis.

| Scenario name | Description |
|---|---|
| Baseline | Original POLES scenario |
| First generation | Above 2005 values all additional biofuels produced from first generation processes |
| Second generation | Above 2005 values all additional biofuels produced from second generation processes |
| No biofuels | No increase in liquid bioenergy share above 2005 values |

et al. (2007), see Table 3. In this baseline, heat and power generation increase nine times between 2000 and 2030 to reach finally 447 million tonnes of oil equivalent (toe) of dry biomass. Also the total liquid biofuel production is projected to increase dramatically, from 0.6% of the total transport energy consumption in 2000 to some 7.5% of the 2030 consumption (28 times). On the other hand, the direct biomass use for energy is predicted to increase relatively slowly between 2000 and 2030, by 26%, representing however by far the largest share bioenergy carrier. In GLOBIOM, the global bioenergy baseline is represented directly by minimum demand constraints.

### 3.2. Scenarios

The scenario analysis in this paper focuses on liquid biofuels and therefore the demand for other bioenergy is assumed not to change. In the baseline, some 60% of liquid biofuels are assumed to be provided by the first generation technologies and 40% by the second generation technologies in 2030. Three other alternative scenarios are considered to analyze the effect of the biofuel conversion pathway and to compare it with the situation of a world with biofuel consumption corresponding to the 2005 levels. All four scenarios are described in Table 4.

Second generation biofuels are not commercially produced yet and their effects and potential relative advantage over the first generation biofuels will depend on where the feedstock comes from, whether it is a by-product or even waste biomass, or whether it is the principal product. In the latter case, the results are likely to depend also on whether this biomass is planted on marginal lands, as some argue that it will be the case, or whether it enters into direct competition with conventional agricultural production. Therefore we consider three different options for the second generation feedstock production:

1. Biomass for second generation biofuels comes from short rotation tree plantations, which can be established either on currently existing cropland or grassland. In this setting plantations enter in competition for land with agricultural production as no agricultural land reserve is assumed.
2. Biomass for second generation is derived only from wood produced in currently existing production, or to production converted, forests, as sawlogs residues or purposely harvested wood for energy. In this case direct competition with agricultural production is eliminated; however, there is competition with the production of conventional forest products.
3. Biomass for second generation biofuels may come from short rotation tree plantations established on non-agricultural land (other natural vegetation). Direct competition with agricultural or forest production is mitigated in this scenario. This last option is included to mimic the potential expansion in marginal lands; "marginal" in the sense that they are not in the base year attractive for agricultural production and they are not forested.

The effects of the above defined scenarios with respect to land use change, resulting greenhouse gas emissions, water, and commodity prices are presented in the next sub-section. To keep the scope of that sub-section in reasonable limits, we focus on the end of the simulation period – year 2030, often compared with the base year 2000.

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**Table 5**
Cumulative deforested area due to cropland expansion in 2030 (Mha) driven by food and bioenergy production.

| Scenario name | Option 1: Crop and grassland | Option 2: Production forests | Option 3: Marginal land |
|---|---|---|---|
| Baseline | 150 | 122 | 105 |
| First generation | 145 | 144 | 130 |
| Second generation | 158 | 90 | 100 |
| No biofuels | 100 | 97 | 77 |

### 3.3. *Results*

#### 3.3.1. *Land use change – impact on deforestation*

GLOBIOM accounts for major land uses. Our scenarios indicate that the most significant land-use changes are expected to be observed with respect to deforestation. Table 5 presents deforestation projections according to the respective scenario assumptions. Deforestation is driven by increased food and bioenergy production, while other drivers of deforestation such as illegal logging are purposely excluded from this analysis. In the "No-Biofuels" scenario the accumulated global deforestation area by 2030 amounts to 100 million hectares (Mha) for Option 1. However under Option 3, where it is allowed to source the biomass for power and heat generation from plantations established on "other natural lands", it does not reach more than 77 Mha. In the first generation biofuel scenario some 145 Mha deforestation are predicted under Options 1 and 2, while Option 3 requires by 11% less forests to be cleared. This indicates that the knock-on leakage effect of cropland and grassland expansion on deforestation is higher compared to a situation where additional other natural land can be used for short rotation plantations easing pressure from agricultural land expanding into forests. The relative difference between the baseline and the pure first generation biofuel case is rather small for Option 1, and largest for Option 3. Additional deforestation occurs when biofuels are introduced. An exception is Option 2, where the second generation pathway leads to an even lower deforestation compared to the no biofuel scenario. This is due to the fact that the feedstock for second generation stems mostly from wood harvesting in existing forests which increases their relative value compared to cropland. When forests are more competitive, deforestation is lower. However, in this option some 350 Mha of otherwise unmanaged forests come into production reducing potentially carbon stocks in these forests (Harmon et al., 1990; Schroeder and Winjum, 1995; Schulze, 2006) and with considerable impacts on biodiversity (Brockerhoff et al., 2008).

The impact of first and second generation biofuels on deforestation depends on the assumptions on feedstock for second generation processes and the respective land availability. If second generation biofuels are to be produced on current agricultural land (cropland and pastures) using short rotation biomass plantations they will indirectly cause some 13 Mha of traditional forest to be deforested above the amount which would be needed if first generation biofuels were used. This is due to the fact that the biophysical yields of sugarcane (C4 plant) are modelled to exceed those of woody plantations if planted on current crop- and grasslands. On the other hand, the balance would point into the opposite direction if second generation biofuels were produced from wood from traditional forests managed in a sustainable way; in that case first generation biofuels would cause some 50% less land to be deforested compared to first generation biofuels.

As a general policy rule, if some marginal non-agricultural land could be used for biofuel production (Option 3), the overall pressure on deforestation would be lowest and second generation biofuels are performing much better with respect to deforestation than first generation biofuels. The overall lowest deforestation is predicted when existing production forests are used for bioenergy purposes *via* second generation biofuels.

#### 3.3.2. *GHG emissions from LUC*

In our analysis, we aim at dynamic full greenhouse gas accounting. However due to basic data constraints we make two simplifying assumptions: (1) Agricultural practices do not have an impact on soil carbon emissions. (2) In the case of deforestation, defined as expansion of cropland into the forest, the total carbon contained in above and below ground living biomass is emitted.

In general, results presented in Table 6 suggest that second generation biofuels improve the global carbon balance even through the LUC related carbon accounts. Under Options 1 and 2, the net emissions are in the "Second generation" scenario lower than in the "No biofuels" scenario, by 7% and 27%, respectively. Despite the fact that Option 3 leads to less deforestation than Option 1, its net emissions from land use change are higher than under Option 1, and also higher than the "No biofuels" emissions. This result is mostly due to the fact that under Option 3, the model chooses to establish 79% of the plantations in "Other Natural Vegetation" with an average net carbon gain of 8 t/ha over 30 years, not creating sufficient sink to compensate for the deforestation. (Under Option 1, 72% of plantations are established on cropland with an average carbon gain of 140 t $CO_2$ over 30 years.)

We confirm the previously expressed worries that first generation biofuels have negative effects on the global carbon balance through iLUC emissions; our simulations suggest that the cumulative net carbon emissions from LUC would be in 2030 by some 70–80% higher in scenario "First generation" than in scenario "No biofuels". The performance is again the worst under Option 3.

To put the iLUC emissions into perspective with respect to the savings in emissions due to substitution of fossil fuels by biofuels, pay back time was adopted as a convenient indicator by several authors (e.g. Fargione et al., 2008; Gibbs et al., 2008; Searchinger et al., 2008). Pay back time is defined as the period over which the annual GHG savings due to substitution of fossil fuels by biofuels equalize the usually fast emissions from land use change. The LUC emissions are calculated from Table 6 as the difference between the biofuel scenarios and the "No biofuels" scenario. Our results for first generation biofuels suggest a pay back period of 22–27 years and thus compare well with the findings of the above mentioned authors (Table 7). We have of course to bear in mind that they represent the average values of converting various ecosystems ranging from tropical forests to temperate grasslands, and that the majority of biofuel comes from an efficient Brazilian sugarcane production.

None of the second generation Options does create any large GHG emission debts. The first two Options actually create net carbon benefits from iLUC, and the small carbon debt generated under Option 3 can be paid back within 2 years.

#### 3.3.3. *Water*

Irrigation water use is an indicator of intensification and production system change in agriculture and thus strongly related

**Table 6**
Cumulative net emissions from land use change for 2000–2030 (Mt $CO_2$ eq.).

| Scenario names | Option 1: Crop and grassland | Option 2: Production forests | Option 3: Marginal land |
|---|---|---|---|
| Baseline | 28,786 | 27,624 | 30,513 |
| First generation | 35,827 | 35,626 | 39,137 |
| Second generation | 19,636 | 14,653 | 23,170 |
| No biofuels | 21,210 | 20,006 | 21,905 |

**Table 7**
Carbon pay back time for different options.

| **Scenario names** | Option 1: Crop and grassland | Option 2: Production forests | Option 3: Marginal land |
|---|---|---|---|
| Baseline | 11 | 10 | 13 |
| First generation | 22 | 24 | 27 |
| Second generation | 0 | 0 | 2 |

**Table 8**
Impact of different production options on irrigation water use in 2030 relative to 2000.

| **Scenario names** | Option 1: Crop and grassland | Option 2: Production forests | Option 3: Marginal land |
|---|---|---|---|
| Baseline | 1.37 | 1.34 | 1.30 |
| First generation | 1.36 | 1.36 | 1.34 |
| Second generation | 1.38 | 1.32 | 1.34 |
| No biofuels | 1.32 | 1.33 | 1.30 |

**Table 9**
Impact of different production options on fuel and crop prices in 2030 relative to 2000 prices.

| Scenario names | Option 1: Crop and grassland | | Option 2: Production forests | | Option 3: Marginal land | |
|---|---|---|---|---|---|---|
| | Fuel price | Crop price | Fuel price | Crop price | Fuel price | Crop price |
| Baseline | 1.18 | 1.29 | 1.35 | 1.25 | 1.12 | 1.21 |
| First generation | 1.14 | 1.27 | 1.14 | 1.27 | 1.14 | 1.24 |
| Second generation | 1.38 | 1.30 | 2.84 | 1.23 | 1.21 | 1.23 |
| No biofuels | 1.10 | 1.23 | 1.10 | 1.23 | 1.09 | 1.21 |

to mitigating the indirect land use change effects of biofuel policies. On average demand for irrigation water is projected to increase by one third even without biofuel expansion (Table 8). The overall irrigation water use due to first generation biofuels would at maximum lead to some 3% increase. This increase would be 1% higher under Option 3 than under Options 1 and 2, because of the lower "No biofuels" reference of the former one. Second generation biofuels do not increase the water demand under Option 2 compared to "No biofuels" scenario. On the other hand, the introduction of second generation biofuels is under Option 1 the most water demanding scenario out of all scenarios, increasing irrigation water consumption by some 4% compared to the "No-biofuels" scenario. This is mainly due to the fact that lower yields from growing trees require more land, which needs to be compensated by higher agriculture yields through increased irrigation.

In general terms the ranking of the land use options and choice of technology is the same as for the deforestation results (Table 5). As expected the "No biofuel" scenarios lead to least water consumption followed by second generation, while first generation requires most irrigation water use – except under the land use Option 1. Relative to the overall increase of irrigation water demand by one third, estimated in our model even for the "No biofuels" scenario, and relative to the technological efficiency gains possible through improved irrigation techniques, the additional global water demand for bioenergy is rather small. However, bioenergy induced competition over water resources could be potentially quite intense in particular in arid and semi-arid regions.

#### 3.3.4. *Prices*

Prices of both first and second generation biofuels start in the simulations at some USD 700 per toe. The prices of first generation biofuels are projected to increase by some 14% over the simulation period and do not differ considerably for the different scenarios (Table 9). On the other hand, the second generation biofuel prices depend considerably on the assumptions we make about the origin of the feedstock. As the most advantageous option appear again biofuels from plantations established on other than agricultural or primary forest land. The most expensive option, with prices nearly tripling between 2000 and 2030 are biofuels based on feedstock from traditional forests.

The strongest effect on the aggregate crop price index, and thus potentially on food security, has development of second generation biofuels on agricultural land, creating additional increase by some seven percentage points compared to the "No biofuels" scenario. On the other hand, if second generation biofuels were sourced from traditional forests; the biofuel production would have negligible effect on crop prices and would outperform the first generation. However, the impact of second generation on wood prices for the forest sector would be in the range of 20% for Option 2.

Crop prices compared to the "No-biofuel" case are by some 4% higher if first generation is used for each land use option. Additional land reserve availability in form of the currently non-agricultural and non-forest lands, would have positive impact also on the crop price development; the crop price index values are the lowest under Option 3.

Please cite this article as: Havlík, P., et al., Global land-use implications of first and second generation biofuel targets. Energy Policy (2010), doi:10.1016/j.enpol.2010.03.030

## 4. Discussion

The sustainability debate on biofuels has largely centred around the possible GHG savings and their impact on global food prices and subsequent association with immediate hunger. To a lesser degree the debate has touched upon the issue of water use. We have therefore applied a bottom-up partial equilibrium framework of the global agriculture, forest and biomass sectors to address these issues. Our findings however, must be interpreted within the limits of the model applied. Scenarios were formulated in such a way that the issue of indirect land use change from biofuel use can be consistently evaluated. We therefore refrained (in the presentation of the scenario results) from the inclusion of biofuel production in poly-generation mode which would produce electricity and heat as marketable co-products. Such analysis would require specific investigation on access to these markets from respective biofuel producers and was deemed out of the scope of this study.

In general, our results indicate that first generation biofuels are performing worst in terms of deforestation (Options 2 and 3), GHG emissions from land use, irrigation water use (Options 2 and 3) and relative price increases of agricultural crops (Options 2 and 3). However, if there are constraints on expansion of the bioenergy sector into forests and other natural lands (land use Option 1) for sourcing woody biomass from managed natural forests and dedicated plantations, respectively, then especially sugarcane based ethanol is superior to second generation biofuels in all aspects studied except for the net land use change GHG emission balance. In particular, the Brazilian ethanol program with its high cane yields and conversion efficiency appears as an interesting example in this respect. For Brazil, our land use Option 1 (cropland and grassland scenario) might be the most appropriate approximation if the avoided deforestation and conservation plans that have been announced by the government will effectively be implemented.[4]

Option 2, which focuses on the expansion of biomass sourcing from existing primary and secondary forests, adopts an occidental paradigm of forest management to be expanded to the pan-tropical belt. There are considerable knowledge gaps and a lack of experience to manage highly species rich tropical forests in a sustainable manner, not only from a biodiversity point of view, but also from a sustainable timber supply standpoint. Our integrated modelling approach assumed a gap disturbance type of regeneration modus similar to European nature like forest management practices in temperate forests. There are however two main draw-backs with this approach. One being high costs of wood production and harvesting due to large infrastructure investments (Putz et al., 2008) – our estimates indicate the second generation prices more than doubled compared with Option 1 – and the danger of subsequent colonization and risk of uncontrolled slash and burn agricultural activities (Nepstad et al., 2001). The other is the conversion of primary old growth forests to production forests, which if wrongly managed might lead to a degradation of ecosystem services, in particular biodiversity (Lewis, 2008). In terms of GHG savings, the second generation bioenergy under Option 2 is the best performer of all scenarios, due to substantially lower deforestation (90 Mha), even lower than the "No biofuels" scenario under this option (97 Mha).

There is substantial uncertainty over the global land reserve which could optionally be deployed for the production of agricultural commodities, serve as a carbon sink via afforestation, be used for biomass production or serve to produce other ecosystem services depending on local needs. Option 3 mimics the effect of such a production reserve which still might exist in 2030. This option is superior to the other two land use options in terms of irrigation water use, deforestation (except for the scenario "Second generation" under Option 2), and crop prices. However, with respect to the currently most debated indicator (GHG savings), this option turns out to be the most inefficient one. The main reason for this result is the rather conservative estimate of current carbon stock on this other land category, which is in line with IPCC default values (Ruesch and Gibbs, 2008), and also the level of estimated afforestation plantation yields play a role.

These parameters might change substantially in the future, in particular when new estimations of carbon stocks based on radar imagery from the ALOS sensor become available. For this land category, which makes up a substantial area of some 510 Mha, we lack however, information on other ecosystem values. Much of these lands might actually not become available due to constraints on ecosystem value preservation beyond carbon and bioenergy. Some of this land might also already be under fuel wood use, which in turn is indirectly captured in our model by the assumption of high carbon losses when clearing these lands.

The scenarios presented in this paper are "pure" biofuel scenarios and therefore the indirect land use emissions projections have to be viewed as unabated. This means that the emissions from deforestation could be avoided by providing a carbon incentive payment or by levying a carbon tax. Thus, indirect land use emissions from biofuels are not an unavoidable evil, but could effectively be managed by appropriate policies. Choke prices for avoiding deforestation are almost entirely in the range of 100 $/ton of carbon. This in turn, however, would raise fuel and food prices considerably and also necessitate additional irrigation. For the latter, we are currently not able to provide analysis as to whether these amounts of irrigation water could actually be supplied on a sustainable basis.

Biofuels, even if they will constitute some 7.5% of total transport energy by 2030, will only add up to a quarter of the total bioenergy sector. According to the POLES baseline scenario, the lion share of biomass will go to direct uses along with heat and power production. Liquid fuels could be produced in poly-generation mode and substitute some of the primary biomass inputs or fossil fuel inputs to produce these energy services. Across the entire biomass sector there are large technological improvement gaps to be closed. These improvements would probably be sufficient to supply all the necessary wood bioenergy to produce second generation biofuels. However, these forms of bioenergy are currently, from an institutional and economic point of view, not accessible for large scale industrial production of biofuels via second generation. Nonetheless, more focus and attention should be given to these types of biomass (mis-)use when regulating biofuels. Regulation of biofuels should thus be comprehensive and be framed in a complete land use approach. The (socio-)economic and GHG savings returns of improving the sustainability of energy access to the poor who rely on fuel wood would be much higher than from making industrial biofuel production more efficient. This is already envisaged in the emerging biofuel sustainability standards currently developed under the coordination of the Round Table for Sustainable Biofuels. Thus, there should be a provision in the life-cycle assessment of biofuels to allow for improvements on the iLUC factor by providing more sustainable energy services to communities impacted by large-scale biofuel projects.

The model structure enables us to directly assess irrigation water needs, which is the single largest use of blue water over the globe (70% of all withdrawals, UN, 2006). Fresh water resources are getting scarcer in many parts of the world because of changes

[4] These, and all the other results presented in this paper, are valid only for the scale of biofuel production investigated here and cannot be extrapolated to any other significantly different scale without further investigation.

Please cite this article as: Havlík, P., et al., Global land-use implications of first and second generation biofuel targets. Energy Policy (2010), doi:10.1016/j.enpol.2010.03.030

in regional water cycles (e.g. droughts), water mismanagement, and increasingly polluted ecosystems. Competition for water is also increasing among agriculture, industry and domestic consumption, especially in countries with increasing population pressure. Irrigation water consumption is an indicator for the intensification and production system change in agriculture. Our projections of increase in irrigation water consumption due to biofuel production remain on the order of percents, hence relatively insignificant at the global scale. These are in line with results presented in other studies (e.g. Rosegrant et al., 2008). Nevertheless, we find that the expansion of irrigation is crucial to maintain the deforested area and crop prices within reported ranges. Our model does not include all relevant constraints which might prohibit this production systems shift in reality. Most of these factors are related to building the respective institutional and physical infrastructure. If these constraints apply, the area deforested increases along with crop and biofuel prices. Thus, any policy promoting biofuels should at least monitor the impacts on water consumption or better yet provide technological improvements to increase irrigation services and crop water productivity. Localization of biofuel production will play an important role too. Any additional competition for water resources may have dramatic impacts in regions where the physical water scarcity persists, and where live nowadays some 1.2 billion people (Molden et al., 2007). But also the biofuel productivity per litre of irrigation water varies considerably between regions as shown by De Fraiture et al. (2008). According to their results, 70 l of irrigation water are necessary to produce 1 l of sugarcane ethanol in Brazil, but 3200 l are required for the same litre of ethanol produced in India.

In recent years, various studies have been published analyzing the impact of biofuel policies on global agriculture commodity markets. Eickhout et al. (2008) have compiled an overview of recently published work on the impact of bioenergy on several commodity prices. They conclude that the modelling set-up varies per exercise, but also the modelling approaches are different. Despite difficulties of comparison it can be concluded that our results on price increases fall well within the median impact strength of the studies i.e. the two to maximum five percent range of price increases on the level of an aggregate crop price index for a policy of 7.5% biofuel mix in all transport fuels. It has to be noted that this price impact is a long-run impact neglecting possible short run effects such as abrupt increases in biofuels due to a policy shock in combination with global weather extreme events such as large scale crop failures in major crop exporting countries. The question whether in the long-run a lower one digit price shock due to biofuel production will lead to less or more undernutrition on a global scale is a question yet to be answered and will surely depend on the context in which biofuels will be introduced. On the one hand biofuels have the tendency to increase food prices and thus reduce the purchasing power of the very poor. On the other hand, price increases might lead to technology improvements and increased farm incomes. The economies of the very poor countries, which are most affected by increased food prices, are mostly dominated by the agricultural sector. Thus, it has yet to be shown which price effect is larger: the direct one pushing consumer prices up, or the indirect one potentially increasing income from agricultural commodity sales, for at least a share of the population. Clearly, biofuel policies can be targeted at mitigating the impacts on undernutrition. The most straightforward policies should include creation of favourable market conditions and land use strategies, as well as initiatives for capacity building (Janssen et al., 2009). Direct quantitative assessment of these wider social issues and effects is beyond the current capacities of the model presented here.

## 5. Conclusion

A new economic global land use model, GLOBIOM, has been presented and applied in this paper, to assess first and second generation biofuels expansion under various settings, focusing on the indirect land use change effects in terms of GHG emissions, irrigation water use, and crop and biofuel prices. The findings presented in this paper have to be considered within the limits of the model and assumptions we have adopted. The first limitation is related to uncertainties of input datasets. For example, Ramankutty et al. (2008) estimate the 90% confidence range of global cropland area to lie between 1220 and 1710 Mha. Availability of consistent economic data at the global scale represents another challenge. There are also structural limitations within the model i.e. a more detailed representation of the livestock sector would improve the assessment of land competition. Despite these limitations we show that the model is able to provide a consistent integrated assessment of land use related environmental and economic effects.

From a GHG emission perspective, we find that second generation biofuels perform the best. However, there are some caveats to be made here. In the case that second generation biofuels are produced from dedicated short rotation plantations on current agricultural land, they perform worse than first generation in all aspects except GHG emissions (gross deforested area, irrigation water use, commodity prices). Rendering second generation biofuels as a sustainable option would mean that feedstocks do not compete with food production. Wood from sustainably managed forests, residues, and wastes must be mobilized, or marginal and abandoned land is to be brought in to production. However, these feedstocks and land are to be selected carefully as their production may infer with other sustainability criteria like biodiversity conservation, erosion protection, or even fuelwood supply for local communities.

To conclude, our analysis shows that biofuel expansion itself is not a silver bullet as it creates a complex system of not only positive but also negative effects/externalities. We have observed that the same level of biofuel production can either be associated with a net carbon sink through land use change, or it may increase net deforestation drastically and create a carbon debt for more than 20 years. The first outcome (net carbon sink) would, in the presented case, not be obtained through a general biofuel mandate because it is accompanied by bioenergy costs twice as high as the second outcome (carbon debt), and thus would be avoided by the industry. To achieve the environmentally positive outcome, forest ecosystem services would have to be explicitly targeted. Similarly, a biofuel induced food price increase will not benefit the poorest populations without appropriate public action. Neither the rural poor, with often limited market access, nor the urban poor, who are typically consumers rather than producers of agricultural commodities, will automatically benefit from the potentially positive income effects of rising prices. Thus, we recommend policy action to focus directly on the positive and negative, environmental and social effects linked with biofuel production, rather than on biofuel production itself.

## Acknowledgements

The research leading to these results has received funding from the European Community's Sixth and Seventh Framework Programme (FP6/FP7) under grant agreement No. 037063 (GOCE), Global Earth Observation - Benefit Estimation: Now, Next and Emerging (GEO-BENE), www.geo-bene.eu; No. 505539, ENSEMBLE-based Predictions of Climate Changes and their Impacts (ENSEMBLES), ensembles-eu.metoffice.com; No. 212535, Climate

Change - Terrestrial Adaptation and Mitigation in Europe (CC-TAME), www.cctame.eu; No. 226487, European approach to GEOSS (EUROGEOSS), www.eurogeoss.eu; (see Article II.30. of the Grant Agreements), from the EU LIFE program funded EC4MACS project (www.ec4macs.eu), from the Integrated Climate System Analysis and Prediction (CliSAP) cluster of excellence at Hamburg University, and from the QUEST/Quatermass project funded by NERC, UK (quest.bris.ac.uk). We want to thank Peter Russ and the POLES team (JRC Sevilla) for providing scenario data on bioenergy use. We are grateful to Robert Zomer (ICRAF) for providing access to the Aridity Index data.

## Appendix A. GLOBIOM – Formal description

Variables

| | |
|---|---|
| $D$ | demand quantity (tonnes, $m^3$, kcal) |
| $W$ | irrigation water consumption ($m^3$) |
| $Q$ | land use/cover change (ha) |
| $A$ | land in different activities (ha) |
| $B$ | livestock production (kcal) |
| $P$ | processed quantity of primary input (tonnes, $m^3$) |
| $T$ | inter-regionally traded quantity (tonnes, $m^3$, kcal) |
| $E$ | greenhouse gas emissions (t $CO_2$ eq.) |
| $L$ | available land (ha) |

Functions

| | |
|---|---|
| $\varphi^{demd}$ | demand function (constant elasticity function) |
| $\varphi^{splw}$ | water supply function (constant elasticity function) |
| $\varphi^{lucc}$ | land use/cover change cost function (linear function) |
| $\varphi^{trad}$ | trade cost function (constant elasticity function) |

Parameters

| | |
|---|---|
| $\tau^{land}$ | land management cost except for water (\$/ha) |
| $\tau^{live}$ | livestock production cost (\$/kcal) |
| $\tau^{proc}$ | processing cost (\$/unit (t or $m^3$) of primary input) |
| $\tau^{emit}$ | potential tax on greenhouse gas emissions (\$/t $CO_2$ eq.) |
| $d^{targ}$ | exogenously given target demand (e.g. biofuel targets) (EJ, $m^3$, kcal, etc.) |
| $\alpha^{land}$ | crop and tree yields (tonnes/ha or $m^3$/ha) |
| $\alpha^{live}$ | livestock technical coefficients (1 for livestock calories, negative number for feed requirements (t/kcal)) |
| $\alpha^{proc}$ | conversion coefficients ($-1$ for primary products, positive number for final products (e.g. GJ/$m^3$)) |
| $L^{init}$ | initial endowment of land of given land use/cover class (ha) |
| $L^{suit}$ | total area of land suitable for particular land uses/covers (ha) |
| $\omega$ | irrigation water requirements ($m^3$/ha) |
| $\varepsilon^{land}$, $\varepsilon^{live}$, $\varepsilon^{proc}$, $\varepsilon^{lucc}$ | emission coefficients (t $CO_2$ eq./unit of activity) |

Indexes

| | |
|---|---|
| $r$ | economic region (27 aggregated regions and individual countries) |
| $t$ | time period (10 years steps) |
| $c$ | country (203) |
| $o$ | altitude class (0–300, 300–600, 600–1100, 1100–2500, $>2500$, in meter above the sea level) |
| $p$ | slope class (0–3, 3–6, 6–10, 10–15, 15–30, 30–50, $>50$, in degree) |
| $q$ | soil class (sandy, loamy, clay, stony, peat) |
| $l$ | land cover/use type (cropland, grassland, managed forest, fast growing tree plantations, pristine forest, other natural vegetation) |
| $s$ | species (37 crops, managed forests, fast growing tree plantations) |
| $m$ | technologies: land use management (low input, high input, irrigated, subsistence, "current"), primary forest products transformation (sawnwood and woodpulp production), bioenergy conversion (first generation ethanol and biodiesel from sugarcane, corn, rapeseed and soybeans, energy production from forest biomass – fermentation, gasification, and CHP) |
| $y$ | outputs (primary: 30+ crops, saw logs, pulp logs, other industrial logs, fuel wood, plantations biomass, processed products: forest products (sawn wood and woodpulp), first generation biofuels (ethanol and biodiesel), second generation biofuels (ethanol and methanol), other bioenergy (power, heat, and gas) |
| $e$ | greenhouse gas accounts: $CO_2$ from land use change, CH4 from enteric fermentation, rice production, and manure management, and $N_2O$ from synthetic fertilizers and from manure management, $CO_2$ savings/emissions from biofuels substituting fossil fuels |

### A.1. Objective function

$$\begin{aligned}\text{Max } WELF_t = &+\textstyle\sum_{r,y}\left[\int \varphi^{demd}_{r,t,y}(D_{r,t,y})d(\cdot)\right]-\sum_{r}\left[\int \phi^{splw}_{r,t}(W_{r,t})d(\cdot)\right]\\ &-\sum_{r,l,\tilde{l}}\left[\int \phi^{lucc}_{r,l,\tilde{l},t}\left(\sum_{c,o,p,q} Q_{r,t,c,o,p,q,l,\tilde{l}}\right)d(\cdot)\right]\\ &-\sum_{r,c,o,p,q,l,s,m}\left(\tau^{land}_{c,o,p,q,l,s,m}A_{r,t,c,o,p,q,l,s,m}\right)\\ &-\sum_{r}\left(\tau^{live}_{r}B_{r,t}\right)-\sum_{r,m}\left(\tau^{proc}_{r,m}P_{r,t,m}\right)\\ &-\sum_{r,\tilde{r},y}\left[\int \phi^{trad}_{r,\tilde{r},t,y}(T_{r,\tilde{r},t,y})d(\cdot)\right]-\sum_{r,e}\left(\tau^{emit}_{t,e}E_{r,t,e}\right)\end{aligned} \quad (1)$$

Exogenous demand constraints

$$D_{r,t,y} \geq d^{targ}_{r,t,y} \quad (2)$$

### A.2. Product balance

$$\begin{aligned}D_{r,t,y} \leq &\sum_{c,o,p,q,l,s,m}\left(\alpha^{land}_{t,c,o,p,q,l,s,m,y}A_{r,t,c,o,p,q,l,s,m}\right)+\alpha^{live}_{r,t,y}B_{r,t}\\ &+\sum_{m}\left(\alpha^{proc}_{r,m,y}P_{r,t,m}\right)+\sum_{\tilde{r}}T_{\tilde{r},r,t,y}-\sum_{\tilde{r}}T_{r,\tilde{r},t,y}\end{aligned} \quad (3)$$

### A.3. Land use balance

$$\sum_{s,m}A_{r,t,c,o,p,q,l,s,m} \leq L_{r,t,c,o,p,q,l} \quad (4)$$

$$L_{r,t,c,o,p,q,l} \leq L^{init}_{r,t,c,o,p,q,l}+\sum_{\tilde{l}}Q_{r,t,c,o,p,q,\tilde{l},l}-\sum_{\tilde{l}}Q_{r,t,c,o,p,q,l,\tilde{l}} \quad (5)$$

$$Q_{r,t,c,o,p,q,l,\tilde{l}} \leq L^{suit}_{r,t,c,o,p,q,l,\tilde{l}} \quad (6)$$

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recursivity equations (calculated only once the model has been solved for a given period):

$$L^{init}_{r,t,c,o,p,q,l} = L^{init}_{r,t-1,c,o,p,q,l} + \sum_{\tilde{l}} Q_{r,t-1,c,o,p,q,\tilde{l},l} - \sum_{\tilde{l}} Q_{r,t-1,c,o,p,q,l,\tilde{l}} \quad (7)$$

$$L^{suit}_{r,t,c,o,p,q,l,\tilde{l}} = L^{suit}_{r,t-1,c,o,p,q,l,\tilde{l}} + \sum_{\tilde{l}} Q_{r,t-1,c,o,p,q,\tilde{l},l} - \sum_{\tilde{l}} Q_{r,t-1,c,o,p,q,l,\tilde{l}} \quad (8)$$

### A.4. Irrigation water balance

$$\sum_{c,o,p,q,l,s,m} (\varpi_{c,l,s,m} A_{r,t,c,o,p,q,l,s,m}) \le W_{r,t} \quad (9)$$

### A.5. GHG emissions account

$$E_{r,t,e} = \sum_{c,o,p,q,l,s,m} \left(\varepsilon^{land}_{c,o,p,q,l,s,m,e} A_{r,t,c,o,p,q,l,s,m}\right) + \varepsilon^{live}_{r,e} B_{r,t} + \sum_{m} (\varepsilon^{proc}_{r,m,e} P_{r,t,m}) + \sum_{c,o,p,q,l,\tilde{l}} \left(\varepsilon^{lucc}_{c,o,p,q,l,\hat{l},e} Q_{r,t,c,o,p,q,l,\tilde{l}}\right) \quad (10)$$

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Please cite this article as: Havlík, P., et al., Global land-use implications of first and second generation biofuel targets. Energy Policy (2010), doi:10.1016/j.enpol.2010.03.030