GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012), doi: 10.1111/j.1757-1707.2012.01188.x

How effective are the sustainability criteria accompanying the European Union 2020 biofuel targets?

STEFAN FRANK*, HANNES BÖTTCHER*, PETR HAVLÍK*§, HUGO VALIN*, ALINE MOSNIER*, MICHAEL OBERSTEINER*, ERWIN SCHMID† and BERIEN ELBERSEN‡

**International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361, Laxenburg, Austria, †University of Natural Resources and Life Sciences, Gregor Mendel Straβe 33, A-1180, Vienna, Austria, ‡Alterra Wageningen UR, Droevendaalsesteeg 4, 6708 PB, Wageningen, The Netherlands, §International Livestock Research Institute (ILRI), P.O. Box 30709, Nairobi 00100, Kenya*

Abstract

The expansion of biofuel production can lead to an array of negative environmental impacts. Therefore, the European Union (EU) has recently imposed sustainability criteria on biofuel production in the Renewable Energy Directive (RED). In this article, we analyse the effectiveness of the sustainability criteria for climate change mitigation and biodiversity conservation. We first use a global agriculture and forestry model to investigate environmental effects of the EU member states National Renewable Energy Action Plans (NREAPs) without sustainability criteria. We conclude that these targets would drive losses of 2.2 Mha of highly biodiverse areas and generate 95 Mt CO_2 eq of additional greenhouse gas (GHG) emissions. However, in a second step, we demonstrate that the EU biofuel demand could be satisfied 'sustainably' according to RED despite its negative environmental effects. This is because the majority of global crop production is produced 'sustainably' in the sense of RED and can provide more than 10 times the total European biofuel demand in 2020 if reallocated from sectors without sustainability criteria. This finding points to a potential policy failure of applying sustainability regulation to a single sector in a single region. To be effective this policy needs to be more complete in targeting a wider scope of agricultural commodities and more comprehensive in its membership of countries.

Keywords: biodiversity, biofuels, GHG emissions, land use change, modelling, Renewable Energy Directive, sustainability criteria

Received 14 March 2012; accepted 26 April 2012

Introduction

Recently, the European Union has set ambitious renewable energy targets with the RED (EC, 2009). As of 2020, 20% of the energy consumption and 10% of the total transport fuel demand should be based on renewable sources, it is expected that the bioenergy sector (biofuels and biomass) will contribute substantially. Even though biofuels offer the potential to reduce fossil fuel based energy production and net emissions (Farrell *et al.*, 2006; Edwards *et al.*, 2008), increasing biofuel demand can result in higher GHG emissions through land use change (Fargione *et al.*, 2008; Searchinger *et al.*, 2008). Furthermore, biofuel production can also lead to biodiversity losses through direct or indirect displacement of natural habitat and other ecologically valuable land (Eggers *et al.*, 2009; Hellmann & Verburg, 2010). In order to ensure GHG emissions savings, prevent biodiversity loss and avoid other negative impacts on the environment, sustainability criteria guiding biofuel production have been included in the RED.

Already numerous studies have analysed effects of biofuels on land use change and GHG emissions at global scale (Al-Riffai *et al.*, 2010; Britz & Hertel, 2011; Havlík *et al.*, 2011). Some studies have also explored the impact of biofuel production on biodiversity inside Europe. Hellmann & Verburg (2010) show that direct effects of the RED biofuel target on European land use are minor while indirect effects can cause up to 8% of additional land use change in Europe compared to a situation without biofuel targets. Eggers *et al.* (2009) demonstrate that more species might suffer habitat loss with increasing biofuel production. However, they conclude that habitat loss due to increasing European biofuel cultivation is much smaller than habitat loss due to overall developments (demographic, economic, political and technological) until 2030. To the best of our knowledge, none of the studies has analysed the effects of biofuel expansion on biodiversity at global scale although there is a serious potential that similarly as the indirect land use change (ILUC) GHG emissions, the ILUC biodiversity loss, will be substantial.

Correspondence: Stefan Frank, tel. + 43 2236 807 218, fax + 43 2236 807 599, e-mail: frank@iiasa.ac.at

Moreover, there is an ongoing discussion about the effectiveness of RED sustainability criteria due to methodological shortcomings of the RED approach. Since the RED only targets the European biofuel sector which is through trade directly linked with the rest of the world (Laborde, 2011), leakage effects in other sectors and countries cannot be prevented, potentially limiting the effectiveness of RED sustainability criteria (Scarlat & Dallemand, 2011; Soimakallio & Koponen, 2011; Van Stappen *et al*., 2011). However, this has never been quantified. We propose to use a global land use modelling framework to understand the environmental impacts of the European biofuel directive on climate change mitigation and biodiversity conservation and assess the effectiveness of European biofuel sustainability criteria in ensuring the latter.

Hence, we apply GLOBIOM (Global Biosphere Management Model), an integrated bottom-up, partial equilibrium model of the global agricultural, bioenergy and forestry sectors. GLOBIOM represents all major land based sectors and therefore is able to account for the direct and indirect effects of land use change implicitly. Together with the detailed representation of technologies, these characteristics make the model a highly valuable tool for assessing impacts of biofuel policies globally. Our approach for exploring effectiveness of sustainability criteria relies on two main steps. First, we use GLOBIOM to look at a Baseline scenario of the biofuel development for the EU and compare it with the Counterfactual scenario assuming no European biofuel increase above 2010 level to analyse the environmental impacts of the European biofuel targets. Second, we assess effectiveness of the RED sustainability criteria by identifying the share of production in the Baseline scenario complying with these criteria and compare it with EU biofuel demand. Computing the 'sustainable' production complying with RED sustainability criteria relies on an ex-post calculation respecting the rationale of the RED.

This article is structured as follows. In the next section we give an overview of the model and the scenario characteristics. This is followed by a detailed description of the sustainability criteria assessment methodology. In the final section of this article we present our results followed by a discussion.

Materials and methods

Model description

GLOBIOM is a global recursive dynamic partial equilibrium bottom-up model integrating the agricultural, bioenergy and forestry sectors. Demand and international trade are represented in this version of the model at the level of 27 EU member states and 23 aggregated world regions outside Europe. Trade calibration method proposed by Jansson & Heckelei (2009) is applied to reconcile observed bilateral trade flows, regional net trade, prices and trading costs for the base year 2000.

Commodity demand is specified as downward sloped function with constant elasticities parameterized using Food and Agriculture Organization of the United Nations Statistics data on prices and quantities, and own price elasticities as reported by Seale *et al*. (2003). The supply side of the model is based on a detailed disaggregation of land into Simulation Units (SimU) – clusters of 5 arcmin pixels belonging to the same country, altitude, slope and soil class and to the same 30 arcmin pixel (Skalský *et al*., 2008). Production technologies at the level of SimU, or their aggregates, are specified through Leontief production functions, which imply fixed input – output ratios.

Crop, grassland, forest and short rotation tree plantation productivity is computed together with related environmental parameters like GHG budgets or nitrogen leaching at the SimU level, either by means of process based biophysical models or by means of downscaling. On the crop production side, GLOBIOM represents 18 major crops and 4 different management systems (irrigated, high input – rainfed, low input – rainfed and subsistence) simulated with the bio-physical process based model EPIC (Environmental Policy Integrated Climate) (Williams, 1995; Izaurralde *et al*., 2006). Parameters for primary forest production such as mean annual increment, maximum share of saw logs in harvested biomass, and harvesting costs are provided by the G4M model (Kindermann *et al*., 2006). Five primary forest products are represented in the model (saw logs, pulp logs, other industrial logs, fuel wood and biomass for energy).

In the model six land use types are represented: cropland, grassland, short rotation tree plantation, managed forests, natural forests and other natural land. Land use change is driven endogenously by demand as well as profitability of the different land based activities.

In the bioenergy sector, GLOBIOM covers first generation and second generation biofuels as well as traditional biomass use and production of heat, electricity and gas from woody biomass. First generation biofuels include bioethanol made from sugar cane, corn and wheat, and biodiesel made from rapeseed, palm oil and soybeans. By-products obtained through biofuel processing are represented in the model. Biomass for second generation biofuels is processed either from existing forests, wood processing residues or from short rotation tree plantations.

In the objective function, 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 subject to resource, technological and policy constraints. For a more detailed description of the model see Havlík *et al*.(2011).

Scenarios

Our Baseline scenario provides an outlook on how bioenergy markets could develop towards 2020 without any sustainability criteria related to biofuel production. The Primes Reference Scenario (Capros *et al*., 2010) is used for European bioenergy demand up to 2020 and NREAPs in 2020. Total European biofuel demand in 2020 amounts to 881 PJ of biodiesel (235 PJ imported), 286 PJ of bioethanol (74 PJ imported) and 31 PJ of 2nd generation biofuels. For the rest of the world we use the POLES (Prospective Outlook on Long-term Energy Systems) Baseline Scenario bioenergy projections (EC, 2011). Other important driving forces in the model are macro-economic developments such as population and gross domestic product growth (EC, 2011).

The Baseline scenario is compared to the Counterfactual scenario assuming no increase in European biofuel demand above 2010 level (biofuel demand fixed to 291 PJ) in order to derive the effects of biofuel expansion on GHG emissions and biodiversity.

Sustainability criteria assessment

The next step of the analysis consists in identifying what share of the biofuel production in the Baseline scenario in 2020 complies with the EU sustainability criteria and can be therefore classified 'sustainable' in the sense of the RED. In GLOBIOM, like in reality, markets are connected and substitution between products and uses is possible. This means that we do not distinguish on the supply side between a crop for food or biofuel as long as it is the same species. All of this makes that direct and indirect effects of land use change in the sense of the RED are simultaneously accounted for and reflected in the results.

Consequently, instead of trying to implement the sustainability criteria ex-ante in the model, we choose an ex-post calculation approach to assess effectiveness of sustainability criteria which apply only to the biofuel sector. Through this approach, we overcome the conceptual difficulty of separating the direct land use change effects of biofuel production as required by the RED.

We represent the most important sustainability criteria specified in the RED following strictly the methodology defined in the RED, using default parameters from the Directive and when available, more precise indicators supplied at the grid cell level by the model.

With respect to GHG emissions savings the following criteria apply:

- Article 17.2: With effect from 1 January 2017, the GHG emission saving from the use of biofuels and bioliquids shall be at least 50%
- Article 17.4: Biofuels and bioliquids shall not be made from raw material obtained from land with high carbon stock namely wetlands and continuously forested areas

With respect to biodiversity protection:

- Article 17.3: Biofuels and bioliquids shall not be made from raw material obtained from land with high biodiversity value namely primary forests and other wooded land, protected areas or highly biodiverse grassland

To evaluate compliance with these criteria, we identify and exclude agricultural production on previously forested, highly biodiverse and high nature value farmland areas. Then the GHG emission saving (mitigation potential) per crop and grid cell is calculated for the remaining agricultural production. Agricultural production that does not comply with the 50% mitigation target is further excluded from the regional 'sustainable' production potential in the sense of the RED. Subsequently, we analyse if the identified 'sustainable' potential is large enough to satisfy European biofuel demand (biofuels processed inside the EU or imported to the EU) within projected trade flow patterns and processing quantities.

Implementation of the GHG emission criteria

We use the life cycle assessment methodology provided by the RED to calculate the GHG emission savings for biofuels for each grid cell. Total emissions are calculated using Eqn (1).

$$\text{Total emissions of fuel} = e_{ec} + e_l + e_p + e_{td} + e_u \qquad (1)$$

where, e_{ec} are the emissions from the extraction or cultivation of raw materials, e_l are the annualized emissions from carbon stock changes caused by land use change, e_p are the emissions from processing, e_{td} are the emissions from transport and distribution and e_u are the emissions from the fuel in use.

Model values are used for emissions from the extraction and cultivation of raw materials for biofuel processing (e_{ec}) and emissions from carbon stock changes caused by land use change (e_l) while default values from RED Annex V are taken for emissions from processing (e_p) and transport and distribution (e_{td}) (Table 1). Emissions from fuel in use are zero (e_u) for biofuels according to RED. Emission savings from soil carbon accumulation, carbon storage and excess electricity from cogeneration as specified in the RED are assumed to be zero and not considered in our calculation.

Emissions from the extraction and cultivation of feedstocks for biofuel processing (e_{ec}) contain emissions from soil N_2O, fertilizer production and fossil fuel use. For emissions related to fertilizer production and application, we use EPIC data for fertilizer inputs harmonized with IFA data (International Fertilizer Industry Association) on global fertilizer use per crop species. Soil N_2O emissions are calculated according to IPCC tier 1 approach using adjusted EPIC fertilizer data and RFA (Renewable Fuels Agency) emission coefficients (RFA, 2009). RFA coef-

Table 1 Default values from the Renewable Energy Directive in g CO_2 eq MJ^{-1}

Feedstock	Processing	Transport and distribution
Corn*	21	2
Palm oil†	18	5
Rapeseed	22	1
Soybean	26	13
Sugar cane	1	9
Wheat*	19	2

*Natural gas as process fuel in CHP plant.
†process with methane capture at oil mill.

ficients are also used for the calculation of emissions from fertilizer production and emissions from fossil fuel use (emissions coefficients and average fossil fuel consumption).

Emissions from land use change (e_l) are based on carbon stocks in above and below ground living biomass estimated for the forest sector by G4M and for grasslands and other natural land taken from Ruesch & Gibbs (2008). Total direct land use change per grid cell is calculated over a 20 year period according to the formula specified in the RED Annex V [Eqn (2)]. Since degraded land is not represented in GLOBIOM, the bonus specified in the RED for biomass production on restored degraded land is not considered. The land use change emissions per grid cell are then allocated to specific crops in a grid cell, according to crop area increase in the Baseline scenario over 2010–2020.

$$e_l = (CS_R - CS_A) \times 3.664 \times \frac{1}{20} \times \frac{1}{P} \qquad (2)$$

where, e_l is the annualized emission from carbon stock changes caused by land use change, CS_R is the carbon stock per unit area associated with the reference land use, CS_A is the carbon stock per unit area associated with the actual land use and P is the productivity of the crop measured in biofuel or bioliquid energy per unit area per year.

Emissions from the extraction and cultivation, land use change and processing[1] are then corrected for the share of the by-products for corn (37%), wheat (40%), rapeseed (41%) and soybean (71%) according to energy content based on the BIOGRACE project (www.biograce.net) and RFA (2009) coefficients. No by-products are considered for palm oil and sugar cane. Default values for emissions from transport and distribution are added and the mitigation potential is calculated using Eqn (3).

$$\text{MITIGATION POTENTIAL} = \frac{(E_F - E_B)}{E_F} \qquad (3)$$

where, E_F is the total emissions from the fossil fuel comparator, E_B is the total emissions from the biofuel or bioliquid.

Implementation of the biodiversity criteria

The Renewable Energy Directive requires biofuel feedstocks not to be obtained from land with high biodiversity value. However, it does not include a map of the highly biodiverse lands. We use high nature value (HNV) farmland areas elaborated by Paracchini *et al.* (2008) to identify agricultural production on highly biodiverse areas in Europe. Paracchini *et al.* define HNV farmland as agricultural land having:

- a high share of semi natural vegetation.
- a mosaic of low intensity agriculture and natural and structural elements.
- a population of rare species or a high proportion of European or world populations.

The HNV farmland distribution map gives the probability to find HNV farmland in a certain area. To determine European HNV farmland in our datasets, we follow the approach suggested by Hellmann & Verburg (2010) and interpret the probability as the actual HNV farmland area in this grid cell, i.e. 30% probability translates into 30% of area in a grid cell is HNV.

Data from United Nations Environment Programme – world Conservation Monitoring Centre (UNEP–WCMC) is used to identify highly biodiverse areas outside Europe. In the Carbon and Biodiversity Report (Kapos *et al.*, 2008), global terrestrial biodiversity areas are identified wherever four or more priority schemes overlap (Conservation International's Hotspots, WWF Global 200 terrestrial and freshwater eco-regions, Birdlife International Endemic Bird Areas, WWF/IUCN Centres of Plant Diversity and Amphibian Diversity Areas).

Overlaying the high biodiversity land maps for Europe and the rest of the world with the land cover maps used in GLOBIOM, we find that in the base year 2000 7.8% of global forests, 5.2% of natural vegetation and 8.1% of grasslands can be considered highly biodiverse. Highly biodiverse primary forests and other natural vegetation are mainly located in Latin America, Sub-Saharan Africa and Asia. A major share of highly biodiverse grasslands is in Europe due to HNV farmland classification. Designated highly biodiverse forest and grassland areas are within the ranges specified in other sources. FAO (2011) reports 7.4% of global forests designated under conservation of biodiversity in 2000 and Hoekstra *et al.* (2005) find 4.6% of temperate and 11.9% of tropical grasslands, savannas and shrublands under conservation.

Results

In the first part of the result section we present impacts of biofuel expansion on GHG emissions and biodiversity by comparing the Baseline to the Counterfactual scenario without biofuel increase in the EU above the 2010 level. In the second part we assess effectiveness of RED sustainability criteria in preventing negative impacts on GHG emissions and biodiversity. Therefore, we first identify the share of production in the Baseline in 2020 complying with RED sustainability criteria. Subsequently, we analyse if the identified 'sustainable' potentials can satisfy European biofuel demand within the projected trade flow patterns. When talking about 'sustainable production' we refer to production complying with the RED sustainability criteria.

Environmental impacts of European biofuel expansion

When contrasting the Baseline to the Counterfactual scenario, total emissions increase by 95 Mt CO_2 eq (+1.3%

[1]We choose natural gas as process fuel in CHP plant as processing path for both corn and wheat in order to be consistent as only for this path a default value for corn is offered in the RED. For palm oil we take the default value for methane capture at oil mill since dissemination of that technology is expected to increase further due to low GHG emissions (Pehnelt & Vietze, 2011).

additional emissions) in 2020. In the Baseline scenario rising emissions from deforestation (84 Mt CO_2 eq), other land use changes (18 Mt CO_2 eq) and from change in cropland management (63 Mt CO_2 eq) and livestock systems (5 Mt CO_2 eq) cannot be compensated for by an increasing carbon sink due to additional establishment of short rotation tree plantations (−17 Mt CO_2 eq) and emission savings due to the replacement of fossil fuel with biofuels (−58 Mt CO_2 eq).

The ILUC factor associated with biofuel production hence amounts to 48 g CO_2 eq MJ^{-1} over 20 years. However, if we distribute emissions over 30 years like most other authors we come up with 32 g CO_2 eq MJ^{-1}. This estimate is within the range of other studies such as Britz & Hertel (2011) who made ILUC estimates of 42 g CO_2 eq MJ^{-1} for European oilseeds biodiesel. Using European crop specific ILUC factors from Laborde (2011) and applying Baseline shares of biofuel feedstocks, the average ILUC estimate would be 29 g CO_2 eq MJ^{-1}.

In addition biofuel expansion is responsible for about 2.2 Mha losses of highly biodiverse areas (+12.4% additional biodiversity loss). Deforestation of highly biodiverse primary forests rises by 0.9 Mha (+9.3%) and additional grassland conversion goes up by 1.0 Mha (+45.8%). Total deforestation rises by 2.4 Mha (+4.2%).

Effectiveness of RED sustainability criteria

Disaggregated 'sustainable' production potential. The disaggregated 'sustainable' production potential refers to the share of Baseline production in 2020 complying with single or combined sustainability criteria (Table 2). For example when we impose only the 50% mitigation target 52% of global corn production is classified as 'sustainable' according to RED methodology. Interestingly, sustainability criteria related to the reduction of deforestation and the conservation of highly biodiverse areas are less stringent criteria than the 50% mitigation target. Consequently, the 50% mitigation target is responsible for the major share of production excluded from the 'sustainable' production potential while only a small share of total production is excluded due to violation of sustainability criteria on direct land use change and conservation of high biodiversity areas. More than 50% of total production of all investigated biofuel feedstocks complies with the sustainability criteria. Especially for rapeseed, soybean, palm oil and sugar cane the overwhelming share of production can be classified 'sustainable' in the sense of the RED.

Table 2 Share of Baseline production in 2020 that is compliant with individual or combined European Union – Renewable Energy Directive criteria.

	DEF (%)	BIO (%)	MIT (%)	DEF + BIO (%)	DEF + BIO + MIT (%)
Corn	97	93	52	90	50
Sugar cane	96	90	93	87	84
Wheat	99	94	56	93	55
Palm oil	100	97	100	97	97
Soybean	99	97	93	96	90
Rapeseed	100	95	81	95	78

DEF, no deforestation (Art. 17.4); BIO, biodiversity conservation (Art. 17.3); MIT, 50% mitigation (Art. 17.2).

One reason for the large biofuel production potential that is already compliant with the RED relates to the fact that deforestation in the Baseline scenario cannot be directly attributed to biofuels as it is mainly driven by grassland expansion into forests. Since only direct land use change effects are considered in the RED methodology, few areas are excluded from the RED specific 'sustainable' production potential. Moreover, areas directly affected by land use change or protected highly biodiverse areas represent only a minor share of total available cropland and areas converted prior to the base year 2000 are not excluded following the RED methodology (this explains the rather surprising result for palm oil, in addition palm oil area expansion until 2020 is small in the Baseline).

Furthermore, allocating emissions to by-products according to energy content reduces emissions significantly for biofuels produced from soybeans, rapeseed, corn and wheat as this method allocates a big share of emissions to the by-products thus limiting the impact of the mitigation criteria. Also high productivity increases the mitigation potential per MJ energy output. Since cropland is usually located on fertile land with high yield potentials, this helps many regions to comply with the 50% mitigation threshold. When looking at areas excluded from the 'sustainable' potential for corn, only 35% of the total corn area is classified sustainable. However, it produces 50% of total supply. Moreover, it has to be noted that biofuel feedstocks differ besides productivity also in regional distribution patterns which is reflected in the results. For example, corn has a lower 'sustainable' production potential than rapeseed since it is produced globally but only a small share of the production in Asia, Africa and Latin America is classified 'sustainable' due to not compliance with the mitigation criteria resulting from low productivity while rapeseed is mainly produced in Europe and Canada where productivity is high and production as a result compliant with the GHG mitigation criteria. However, this does not imply that rapeseed production is more 'sustainable' than corn as it shows only that a larger part of the global production is classified 'sustainable' in the sense of the RED.

Applying uniform processing default values also brings controversial results for palm oil since a large share of palm oil production is classified 'sustainable'. Applying the higher processing default values for palm oil (49 g CO_2 eq MJ^{-1}) from the RED (processing path where no process fuel use is specified instead of methane capture at oil mill) no production is classified 'sustainable'. This highlights the importance of choosing actual values over standardised default values.

Aggregated 'sustainable' production potential. European bioethanol and biodiesel demand in 2020 amounts to 286 PJ and 881 PJ respectively, and has to be processed from feedstocks complying with RED sustainability criteria. Table 3 presents the share of the total European biofuel demand (1.167 PJ) that could be satisfied from 'sustainable' production in a region per feedstock type. For example, Latin America could supply 39% of total European biofuel demand in 2020 with its 'sustainable' soybean production potential. Globally, 'sustainable' production in the sense of the RED can produce more than 10 times the 2020 EU biofuel demand.

Especially crops for bioethanol production like sugar cane and corn have large 'sustainable' production potentials to satisfy the European biofuel demand. These potentials are located in the US, Brazil and South and South East Asia. In the US, the huge 'sustainable' potential for corn results mainly from high productivity and a rather low default value for emission from biofuel processing, although it is generally accepted in the literature that corn based bioethanol in the US has negative impacts on GHG emissions due to indirect land use change effects and is therefore considered not as sustainable (Fargione *et al.*, 2008; Searchinger *et al.*, 2008; Hertel *et al.*, 2010; Mosnier *et al.*, 2012).

The 'sustainable' production potentials of biodiesel feedstocks outside Europe are located in Canada and Asia (rapeseed), South and South East Asia (palm oil) as well as in Brazil and the US (soybean). About 75% of EU biofuel demand is expected to come from biodiesel, which offers limited 'sustainable' feedstock production potential inside the EU (rapeseed can at most supply 33% of the biodiesel mandate). Consequently, a substantial share of biodiesel feedstocks has to be imported to Europe. For Brazil, the large 'sustainable' potential for soybean can be explained by the fact, that deforestation in Latin America is mainly driven by grassland expansion in the model. Therefore no land use change emissions from deforestation are allocated particularly to soybean production since only direct effects are considered in the RED methodology. However, besides grassland expansion also soybean production is an important driver of deforestation in Amazon (Fearnside, 2005; Morton *et al.*, 2006; Nepstad *et al.*, 2006).

Supplying EU biofuel demand from 'sustainable' sources. The NREAPs specify which share of the demand will be satisfied from domestically refined biofuels, and which share of biofuels will be imported. Table 4 illustrates the methodology used in the ex-post calculation of the feasibility to satisfy European biofuel demand as specified in the NREAPs – consisting of biofuels refined inside the EU (upper part of the table) and biofuel imports (lower part of the table) – from 'sustainable' sources within projected Baseline trade flows and processing quantities.

With respect to the sustainable supply of biofuels refined in the EU in the Baseline in 2020, 72% of biofuel demand refined in the EU is satisfied from rapeseed, 21% from corn, 4% from soybean and 3% from wheat. While bioethanol demand refined in the EU (column 2) can be met from domestic 'sustainable' feedstock production (column 1 > column 2), biodiesel demand

Table 3 Share of 'sustainable' production potential per region and feedstock compared to total European biofuel demand in 2020

	Corn (%)	Wheat (%)	Sugar cane (%)	Rapeseed (%)	Soybean (%)	Palm oil (%)	Total (%)
EU27	33	63	0	25	0	0	120
Middle East and North Africa	15	15	0	0	1	0	31
Sub-Saharan Africa	6	3	10	0	0	4	23
Pacific	0	9	10	9	0	0	28
Former USSR	0	62	0	1	0	0	63
China	0	2	9	25	13	0	49
South and South East Asia	2	55	111	5	0	77	250
Latin America	29	10	80	0	39	3	162
Canada	5	0	0	26	0	0	31
US	246	54	7	0	45	0	352
World	337	274	228	91	98	84	1111

Table 4 Meeting of European Baseline biofuel demand from 'sustainable' sources in 2020 by distributing sustainable production potentials in the rest of the world to biofuel demand in the European Union

	EU			Rest of the world		
	Sustainable production potential 1	Demand 2	Import requirements 3 = 2-1	Sustainable production potential 4	Total exports to the EU 5	Sustainable exports to the EU 6
EU SUSTAINABLE FEEDSTOCK BALANCE						
EU refined biodiesel in Mt feedstocks						
From rapeseed	19.2	40.4	21.3	50.6	26.8	24.7
From soybean	0.0	5.2	5.2	190.1	23.3	21.5
EU refined bioethanol in Mt feedstocks						
From corn	46.1	21.9	0.0			
From wheat	93.3	3.8	0.0			
EU SUSTAINABLE BIOFUEL TRADE BALANCE						
Imported biodiesel in PJ						
From rapeseed				769		32
From soybean				1,142		252
From palm oil				976		94
Total			235	2,887	235	378
Imported bioethanol in PJ						
From corn				3,555		774
From sugar cane				2,657		383
From wheat				2,462		3
Total			74	8,674	74	1,160

Correction added on 17 July 2012 after online publication: The total for 'Sustainable exports to the EU' has been changed from 1.160 to 1,160.

refined in the EU for rapeseed and soybean has to rely on 'sustainable' feedstock imports (column 3 = column 2 – column 1). Since European feedstock production complying with the RED sustainability criteria is smaller than the feedstock demand for biodiesel processing, about 21.3 Mt of rapeseed and 5.2 Mt of soybean have to be imported from the rest of the world. The next step is to analyse whether these import requirements for rapeseed and soybean can actually be met through trade from 'sustainable' sources outside Europe.

Total exports to the EU (column 5) represent total Baseline exports to Europe in 2020 and include exports for biofuel processing, human consumption and animal feeding. The 'sustainable' exports to the EU (column 6) are the maximum quantity of 'sustainable' feedstocks or biofuels that can be exported to Europe. Sustainable feedstock imports are limited either by the 'sustainable' production potential in the exporting region (column 4) (a region cannot export more 'sustainable' feedstock than what is being produced in that region) or by the projected total exports to the EU (column 5) (a region cannot export more 'sustainable' feedstocks to the EU than the total trade flow volume to the EU in the Baseline) i.e. even though the 'sustainable' production potential for rapeseed amounts to 50.6 Mt in the rest of the world, only 24.7 Mt can be exported to Europe for biofuel processing since in the Baseline scenario projected total exports to the EU sum up to only 26.8 Mt. It is to be noted that this calculation is conducted at the regional level and then aggregated to the rest of the world, which is the reason why projected total exports to the EU and the 'sustainable' exports to the EU deviate. Basically, this rigid procedure ensures that European sustainable feedstock demand is satisfied just by reallocating 'sustainable' supply within the limits of the trade flows as obtained in the Baseline model solution.

Overall, European biofuel processing demand can be met from 'sustainable' sources, since the 'sustainable' exports to Europe from the rest of the world exceed the import requirements. Processing demand for rapeseed can be satisfied by importing 'sustainable' rapeseed from Canada and Asia. About 42% of the 'sustainable' production potential in the rest of the world has to be imported to Europe filling up 80% of the projected rapeseed imports to Europe.

In Europe, soybean prices decrease due to the availability of cheap by-products from biofuel processing such as rapeseed cake and corn dry distiller grains, which can substitute soybean as a typical feedstock for animals. Since European farmers are not competitive at low prices, soybean processing demand in the EU (5.2 Mt) has to be met exclusively by imports. However, since large 'sustainable' production potentials are located in Latin America and the US and sufficient trade flows to Europe are projected, European soybean processing demand can be satisfied from 'sustainable' sources. Overall, only 3% of the total 'sustainable' production potential in the rest of the world has to be imported to Europe using 23% of the total projected imports to Europe in 2020.

With respect to biofuels refined outside of the EU and then imported (235 PJ of biodiesel and 74 PJ of bioethanol according to the NREAPs – lower part of column 3), they also have to comply with RED sustainability criteria. For biofuel imports, the 'sustainable' exports to the EU are limited by the 'sustainable' production potential (column 4) less the 'sustainable' exports of biofuel feedstocks to the EU (upper part of column 6) and by the projected Baseline processing quantities in 2020 in a region. For example, the 'sustainable' rapeseed production potential in the rest of the world amounts to 50.6 Mt of which 24.7 Mt can be exported to Europe to satisfy the EU refined biodiesel demand from rapeseed. The remaining 25.9 Mt are potentially available for biodiesel processing in the rest of the world. However, in the Baseline in 2020 actually only 2.1 Mt of rapeseed are refined to biodiesel outside Europe and therefore the 'sustainable' exports to the EU for biodiesel from rapeseed amounts only to 32 PJ. Overall, 1.6 times more biodiesel (column 6 divided by column 5) and 15 times more bioethanol than what needs to be imported to Europe, can be processed sustainably in the rest of the world. Hence, besides EU refined biofuels also European biofuel imports can be comfortably supplied from 'sustainable' sources in the Baseline scenario.

Discussion

The sustainability debate on biofuels has mainly focused on GHG emissions related to direct and indirect land use changes. Recently, concerns have been raised about negative impacts of biofuels on biodiversity and habitat loss. Hence, we used GLOBIOM to assess the impacts of European biofuel mandates on GHG emissions and global biodiversity and effectiveness of RED sustainability criteria on the latter.

Our results indicate that European biofuel targets have a negative impact on high biodiversity areas and global GHG balance as biofuel expansion according to the NREAP targets would generate losses of 12.4% of high biodiversity areas. We identified in our Baseline scenario large feedstock potentials for bioethanol production in North America, Brazil and Asia complying with RED sustainability criteria (without taking additional action). Globally, 'sustainable' production in the sense of the RED could supply more than 10 times the EU 2020 biofuel demand if reallocated from sectors without sustainability criteria. Substantial shares of bioethanol feedstock and to a smaller amount biodiesel feedstocks comply with the sustainability criteria defined in the RED. Hence, EU refined biofuels and biofuel imports can be supplied from 'sustainable' sources complying with the RED sustainability criteria.

However, the calculated mitigation and 'sustainable' production potentials complying with RED sustainability criteria have to be considered within the limits of the methodology and uncertainty of the data used. First, the total emissions are sensitive to the setting of default values. Since the computation of N_2O and carbon stock changes depends on various local factors (cropping system, climate, reference land use system etc.), they are difficult to quantify and highly uncertain. Nevertheless, their contribution to total GHG emissions from biofuel production can form a substantial share (Edwards *et al.*, 2008; Reijnders & Huijbregts, 2011; Van Stappen *et al.*, 2011). Different ways of allocating emissions to the by-product (i.e. by price or physical unit) influence results of life cycle assessment too (Cherubini *et al.*, 2011; Mala & Freire, 2011). Consequently, the allocation of emissions to by-products based on energy content, the chain step where the energy allocation takes place (Van Stappen *et al.*, 2011) as well as the magnitude of by-product supply coefficient have an impact on the calculated mitigation potential. This highlights the sensitivity of the life cycle assessments. Results may change when using different emission coefficients, regional actual values instead of default values for processing, transport and distribution. Moreover, Soimakallio & Koponen (2011) and the EEA (2011) conclude, that applying the RED methodology cannot ensure reduced GHG emissions from biofuel production due to methodological choices such as the subjective setting of system boundaries in the life cycle assessment or the not consideration of ILUC effects.

Despite these uncertainties and shortcomings of the RED, our results enable us to conclude, that sustainability criteria of the RED will have little or no effect on global agricultural production systems due to leakage effects in the food and animal feed sector and the biofuel sector outside Europe. Since the 'sustainable' production potential is too large compared to the 'sustainable' feedstock demand resulting from European biofuel mandate, the 'sustainable' production will be easily redirected to the demand without changing the environmental impacts compared to a situation without sustainability criteria. Consequently, RED sustainability criteria are ineffective in ensuring GHG mitigation and preventing loss of highly biodiverse areas in agriculture as they only cover a small part of the global agricultural feedstock demand.

Our findings are in agreement with other studies that also stress the possibility of leakage effects due to ILUC when limiting sustainability criteria only on the biofuel sector (Van Stappen *et al.*, 2011). Some authors propose extending sustainability standards to all agricultural production (Edwards *et al.*, 2008; Gallagher, 2008; Scarlat & Dallemand, 2011). Hence, to be effective this policy needs to be more complete in targeting a wider scope of agricultural commodities and more comprehensive in its membership of countries. In addition, a combination with wider land use change policies targeting all drivers of land use change and not only the biofuel sector – such as reduction of emissions from deforestation and forest degradation (REDD) – may improve overall effectiveness of policies in achieving biodiversity conservation since deforestation is an important driver for biodiversity loss (Fearnside, 2005; Strassburg *et al.*, 2012).

Acknowledgements

This publication was funded by the BIOMASS FUTURES project (Biomass role in achieving the Climate Change & Renewables EU policy targets. Demand and Supply dynamics under the perspective of stakeholders – IEE 08 653 SI2. 529 241, www.biomassfutures.eu) funded by the European Union's Intelligent Energy Programme.

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7) under grant agreement n° 244766, Paradigm shifts modelling and innovative approaches (PASHMINA), www.pashmina-project.eu.

References

Al-Riffai P, Dimaranan B, Laborde D (2010) *Global Trade and Environmental Impact Study of the EU Biofuels Mandate*. International Food Policy Research Institute, Washington, D.C.

Britz W, Hertel TW (2011) Impacts of EU biofuels directives on global markets and EU environmental quality: an integrated PE, global CGE analysis. *Agriculture, Ecosystems & Environment*, **142**, 102–109.

Capros P, Mantzos L, Tasios N, De Vita A, Kouvaritakis N (2010) *EU energy trends to 2030 — UPDATE 2009*. 184 pp EUROPEAN COMMISSION Directorate-General for Energy in collaboration with Climate Action DG and Mobility and Transport DG.

Cherubini F, Strømman AH, Ulgiati S (2011) Influence of allocation methods on the environmental performance of biorefinery products - A case study. *Resources, Conservation and Recycling*, **55**, 1070–1077.

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.

EC (2011) *Impact Assessment - A Roadmap for Moving to a Competitive Low Carbon Economy in 2050*. European Commission (EC), Brussels.

Edwards R, Szekeres S, Neuwahl F, Mahieu V (2008) *Biofuels in the european context: facts and uncertainties*. Joint Research Centre Institute for Energy (JRC-IE), Joint Research Centre Institute for Environment and Sustainability (JRC-IES).

EEA (2011) *Opinion of the EEA Scientific Committee on Greeenhouse Gas Accounting in Relation to Bioenergy*. European Environment Agency, Copenhagen.

Eggers J, Tröltzsch K, Falcucci A *et al.* (2009) Is biofuel policy harming biodiversity in Europe? *GCB Bioenergy*, **1**, 18–34.

FAO (2011) *State of World's Forests*.United Nations Food and Agricultural Organisation (FAO), Rome.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 1235–1238.

Farrell AE, Plevin RJ, Turner BT, Jones AD, O'hare M, Kammen DM (2006) Ethanol can contribute to energy and environmental goals. *Science*, **311**, 506–508.

Fearnside PM (2005) Deforestation in Brazilian Amazonia: history, rates, and consequences. *Conservation Biology*, **19**, 680–688.

Gallagher E. (2008) *The Gallagher Review of the Indirect Effects of Biofuels Production*. Renewable Fuels Agency, St Leonards-on-Sea, East Sussex.

Havlík P, Schneider UA, Schmid E *et al.* (2011) Global land-use implications of first and second generation biofuel targets. *Energy Policy*, **39**, 5690–5702.

Hellmann F, Verburg PH (2010) Impact assessment of the European biofuel directive on land use and biodiversity. *Journal of Environmental Management*, **91**, 1389–1396.

Hertel TW, Golub AA, Jones AD, O'hare M, Plevin RJ, Kammen DM (2010) Effects of US maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses. *BioScience*, **60**, 223–231.

Hoekstra JM, Boucher TM, Ricketts TH, Roberts C (2005) Confronting a biome crisis: global disparities of habitat loss and protection. *Ecology Letters*, **8**, 23–29.

Izaurralde RC, Williams JR, Mcgill WB, Rosenberg NJ, Jakas MCQ (2006) Simulating soil C dynamics with EPIC: model description and testing against long-term data. *Ecological Modelling*, **192**, 362–384.

Jansson T, Heckelei T (2009) A new estimator for trade costs and its small sample properties. *Economic Modelling*, **26**, 489–498.

Kapos V, Ravilious C, Campbell A *et al.* (2008) *Carbon and Biodiversity: A Demonstration Atlas*. UNEP-WCMC, Cambridge, UK.

Kindermann GE, Obersteiner M, Rametsteiner E, Mccallum I (2006) Predicting the deforestation-trend under different carbon-prices. *Carbon Balance and Management*, **1**, art. no. 15.

Laborde D (2011) *Assessing the Land Use Change Consequences of European Biofuel Policies Final Report*. IFPRI, Washington, DC, USA.

Mala J, Freire F (2011) Life-cycle studies of biodiesel in Europe: A review addressing the variability of results and modeling issues. *Renewable and Sustainable Energy Reviews*, **15**, 338–351.

Morton DC, Defries RS, Shimabukuro YE *et al.* (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 14637–14641.

Mosnier A, Havlík P, Valin H *et al.* (2012) *The Net Global Effects of Alternative U.S. Biofuel Mandates: Fossil Fuel Displacement, Indirect Land Use Change and the Role of Agricultural Productivity Growth*.Nicholas Institute for Environmental Policy Solutions, Duke University.

Nepstad DC, Stickler CM, Almeida OT (2006) Globalization of the Amazon soy and beef industries: opportunities for conservation. *Conservation Biology*, **20**, 1595–1603.

Paracchini M, Petersen J, Hoogeveen Y, Bamps C, Burfield I, Van Swaay C (2008) *High Nature Value Farmland in Europe. An Estimate of the Distribution Patterns on the Basis of Land Cover and Biodiversity Data. European Commission Joint Research Centre*. Institute for Environment and Sustainability. Office for Official Publications of the European Communities, Luxembourg.

Pehnelt G, Vietze C (2011) *Recalculating Default Values for Palm Oil*. JENA Economic Research Papers, Jena.

Reijnders L, Huijbregts MaJ (2011) Nitrous oxide emissions from liquid biofuel production in life cycle assessment. *Current Opinion in Environmental Sustainability*, **3**, 432–437.

RFA (2009) *Carbon and Sustainability Reporting Within the Renewable Transport Fuel Obligation; Technical Guidance Part Two Carbon Reporting – Default Values and Fuel Chains*. RFA - Renewable Fuels Agency, St Leonards-on-Sea, East Sussex.

Ruesch A, Gibbs HK (2008) *New IPCC Tier-1 Global Biomass Carbon Map For the Year 2000*. Available online from the Carbon Dioxide Information Analysis Center http://cdiac.ornl.gov, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Scarlat N, Dallemand JF (2011) Recent developments of biofuels/bioenergy sustainability certification: a global overview. *Energy Policy*, **39**, 1630–1646.

Seale J, Regmi A, Bernstein J (2003) *International Evidence on Food Consumption Patterns*. ERS/USDA, Technical Bulletin No.1904. ERS/USDA, Washington, DC, USA.

Searchinger T, Heimlich R, Houghton RA *et al.* (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240.

Skalský R, Tarasovičová Z, Balkovič J *et al.* (2008) *GEO-BENE Global Database for Bio-Physical Modeling v. 1.0 - Concepts, Methodologies and Data*. The GEO-BENE database report. International Institute for Applied Systems Analysis (IIASA), Austria.

Soimakallio S, Koponen K (2011) How to ensure greenhouse gas emission reductions by increasing the use of biofuels? – suitability of the European union sustainability criteria. *Biomass and Bioenergy*, **35**, 3504–3513.

VanStappen F, Brose I, Schenkel Y (2011) Direct and indirect land use changes issues in European sustainability initiatives: state-of-the-art, open issues and future developments. *Biomass and Bioenergy*, **35**, 4824–4834.

Strassburg B, Rodrigues A, Gusti M *et al.* (2012) Impacts of incentives to reduce emissions from deforestation on global species extinction. *Nature Climate Change*, **2**, 350–355.

Williams JR (1995) The EPIC model. In: *Computer Models of Watershed Hydrology* (ed. Singh VP), pp. 909–1000. Water Resources Publications, Highlands Ranch, Colorado.