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Title:

Effects of land-use change on the carbon balance of 1st generation biofuels: An analysis for the European Union combining spatial modeling and LCA

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Abstract

Biofuels are considered as an important option for the mitigation of climate change. However, the negative impact of land-use change (LUC) on soil and vegetation carbon pools may jeopardize the potentially achievable savings of greenhouse gas (GHG) emissions. In this study the impact of GHG emissions from LUC on the overall GHG performance of 1st generation biofuels was analyzed for the European Union (EU). The scenario-based analysis was done by coupling a spatial land-use model to a Life Cycle Assessment (LCA) of biofuels. The biofuel demand in the scenarios was derived from figures for the transport sector of the EU-27 Member States. The calculation of GHG emissions was performed with a Geographic Information System. Finally, these results were integrated into the LCA approach of the EU Renewable Energy Directive (RED). Without taking LUC into account, the average GHG emission saving compared to fossil fuel use amounts to ~50%. In this case the mandatory 35% emission saving target laid down in the RED would be fulfilled. If LUC is considered, this target is reached under none of the simulated biofuel scenarios. In the most realistic scenario the GHG emission savings from 1st gen. biofuel use compared to fossil fuel use range between -2% and 13%. Based on our findings, we conclude that national policy plans for biofuel use should be reconsidered and revised as in their current form they do not provide an adequate measure for the mitigation of global warming on EU-level.

Keywords: Biofuels; Spatial model; Land-use change; GHG emissions; LCA; European Union

1. Introduction

The Renewable Energy Directive (RED)[1] *on the promotion of the use of energy from renewable sources* [1] includes a specific target for the European Union (EU) transport sector. 10% of the energy consumption in transport has to be covered by renewable sources in each Member State by 2020. Besides reducing the dependency on oil imports and fostering the development of rural areas, the aim of this regulation is to diminish transport related greenhouse gas (GHG) emissions. This study addresses the last issue. Currently the share of renewable energy sources in EU road transport amounts to 3.5%, with 1st gen. biofuels as the most important renewable source [2]. Of all 1st gen. biofuels consumed in EU road transport, biodiesel makes up the largest share (72%), followed by bioethanol (19%) and other biofuels (9%). The major part of 1st gen. biofuels consumed in the EU is produced domestically from crops such as rapeseed, wheat, maize and sugar beet. Biodiesel imports, primarily from the US, account for 22%, bioethanol imports, primarily from Brazil, account for 35%. The GHG emissions associated with biofuels are often assessed with the help of Life Cycle Assessment (LCA), a technique intended to take into account “the potential environmental impacts of a product system throughout its life cycle” [3].

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[1] RED: Renewable Energy Directive, EU: European Union, GHG: Greenhouse gas, LCA: Life Cycle Assessment, LUC: land-use change, NREAP: National Renewable Energy Action Plan, GIS: Geographic Information System, SUE: Sustainability Eventually, TC: Technological change

But common LCA practice typically does not assess impacts resulting from direct or indirect land-use change (LUC) [4–7]. When GHG emissions from LUC are *not* taken into account IEA [8] estimates GHG emission savings from 1st gen. biofuel use compared to fossil fuel use between -20% and 120%, while European Commission and UK RFA [1,9] estimate a range of 16 - 71%.

Direct LUC due to biofuel production occurs if land (e.g. forest or grassland) is converted to cropland for the production of biofuels. Direct LUC is strictly regulated in the sustainability criteria of the RED [1]. Indirect LUC occurs if biofuel production takes place on existing cropland and for the production of food additional non-cropland has to be converted to cropland. In this study we account for both, direct and indirect LUC, but we do not explicitly differentiate between them. Since the carbon stocks in soil and vegetation are closely linked with the land-use type, they also change if LUC takes place. A decrease in these carbon stocks results in the release of carbon dioxide to the atmosphere [10]. Therefore LUC has an impact on the GHG performance of biofuels.

According to Annex V of the RED [1] GHG emissions resulting from LUC have to be included in the LCA of biofuels. Since the location of LUC is relevant for the calculation of GHG emissions, the assessment of LUC should be spatially explicit [4].

There are several studies concerning GHG emissions associated with LUC due to biofuel production. Bowyer [11] estimates GHG emissions from LUC between 44 and 77 $MtCO_{2eq}\ a^{-1}$ on EU-level by applying conversion factors to biofuel figures taken from the National Renewable Energy Action Plans (NREAPs) of the EU Member States [12]. The usage of conversion factors represents a non-spatially explicit form of accessing LUC and associated GHG emissions. DG Energy [13] carried out a literature review, taking into account 22 LUC modeling exercises, for the European Commission concerning the impact of LUC on the GHG performance of biofuels. They criticize that all of the reviewed models neglect the option of biofuels not being produced at all and that it is unclear throughout all evaluated models how the assumed quantities of biofuel production are obtained. Moreover, none of the reviewed models considers the mandatory EU GHG emission saving target laid down in the RED and the possibility of GHG emission saving improvements by 2020. Finally, there are numerous differences in the method of carbon stock calculation among the reviewed models.

In this paper we describe our approach to overcome the shortcomings listed above. We use the spatially explicit simulation model LandSHIFT [14,15] to determine LUC due to 1st gen. biofuel production on a 5 arc minutes grid map of the EU-27 Member States[2]. Based on standard values for carbon stocks in soil and vegetation taken from the EU's RED [1] we calculate the GHG emissions from LUC for each grid cell by employing Geographic Information System (GIS) software. We couple the spatial model to a LCA of biofuels by integrating the calculated GHG emissions from LUC, as an elementary flow, into the LCA approach of the EU's RED. In order to determine the overall GHG performance of biofuels we calculate the GHG emission saving indicator, which is directly comparable to the mandatory target laid down in the RED. Our analysis uses scenarios of 1st gen. biofuel production and compares them to a baseline scenario without biofuel use. The biofuel demand in the biofuel scenarios is based on figures for the period 2005-2020 taken from the NREAPs. Moreover, we assume that technological change (TC) increases crop yields and decreases GHG emissions in the biofuel industry.

In the methods and materials section we describe the LCA approach of the RED, the LandSHIFT model and its validation, the design of our study, the calculation of GHG emissions from LUC and the impact assessment. Section 3 presents the results of our study on aggregate EU-level as well as on Member State level: LUC, GHG emissions from LUC and an indicator for

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[2] The study area comprises the EU-27 Member States except Malta, Cyprus and Luxembourg which have been excluded because the 5 arc minutes resolution we use does not allow for analysis of LUC in those countries.

the GHG performance of biofuels. In section 4 the study results are discussed. The paper ends with a short conclusion.

2. Methods and materials

2.1 Life cycle assessment

In the RED [1], the LCA of fuels and biofuels regarding GHG emissions is defined as shown in equation 1[3]. All emissions are expressed in gCO_{2eq} MJ^{-1}.

(1)

where

$E_{B/F}$ = total emissions from the use of biofuel (B) or fossil fuel (F)
e_{ec} = emissions from the extraction or cultivation of raw materials
e_l = annualised emissions from carbon stock changes caused by LUC
e_p = emissions from processing
e_{td} = emissions from transport and distribution
e_u = emissions from the fuel in use

Since the methodology takes into account all GHG emissions from the fuel extraction or crop cultivation to the movement of the car, the LCA approach laid down in the RED can be categorized as well-to-wheels analysis. Compared to other approaches, like well-to-tank or tank-to-wheels, well-to-wheels is the most holistic approach in determining the impact of fuels [16]. The system boundaries of the LCA system are clearly defined: "Emissions from the manufacture of machinery and equipment shall not be taken into account" [1], which is common practice for well-to-wheels analyzes [16]. In order to compare the GHG emissions of fossil fuels and biofuels, a well-to-wheels analysis is performed for both, fossil fuels and biofuels.

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[3] In the framework of this study emission savings from carbon capture, excess electricity and soil carbon accumulation via improved agricultural management are assumed to be zero. Therefore the corresponding terms have been excluded from the equation.

In the case of fossil fuels, the LCA might include GHG emissions from the extraction of crude oil (e_{ec}), the processing of crude oil to fuel (e_p), the transport of fuel to a petrol station (e_{td}) and finally the combustion of fuel in an engine (e_u). In the framework of this study the GHG emissions from fossil fuel usage are assumed to be 83.8 gCO_{2eq} MJ^{-1}, which is the standard value for the fossil fuel comparator (E_F) provided in the RED [1].

In the case of biofuels, the LCA might include GHG emissions from the cultivation (e_{ec}), the carbon stock changes caused by LUC (e_l), the processing of crops to biofuel (e_p) and the transport of biofuel to a petrol station (e_{td}). GHG emissions from the fuel in use (e_u) are assumed to be zero in the case of biofuels [1]. In this study, we use typical GHG emission values for e_{ec}, e_p and e_{td} from the RED according to the biofuel production pathways considered in our analysis[4]. For the remaining GHG emissions from carbon stock changes caused by LUC (e_l) the RED does not provide default values. Instead of a rough estimate, in this study we use the spatially explicit simulation model LandSHIFT in combination with GIS software in order to determine e_l in a more detailed way. The calculation of e_l is described in sub-section 2.5.

2.2 Modeling of land-use change

Computations of changes of cropland area are carried out with the spatially explicit land-use model LandSHIFT. The model is fully described in Schaldach et al. [14] and has been tested in different world regions [15,17]. It is based on the concept of land-use systems [18] and couples components that represent the respective anthropogenic and environmental sub-systems.

In our study, we have included sub-modules to simulate the change of cropland area (AGRO-module) and crop productivity (productivity-module). Changes of cropland area are calculated on a raster with the spatial resolution of 5 arc-minutes, i.e. the cell size is highest at the equator (~ 9 km x 9 km) and gets smaller towards the poles (~ 6 km x 7 km in central Europe). Each cell is

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[4] See Table 6

assigned to the territory of one European country. Cell-level information includes the state variables “dominant land-use type” and a set of parameters that describe its landscape characteristics (e.g. terrain slope), available road infrastructure and zoning regulations. The land-use data is derived from the EU's CORINE Land Cover project [19]. Information on crop productivity of each grid cell is derived from raster maps displaying the potential yields under rain-fed and irrigated conditions for 11 crop types (wheat, maize etc.), calculated with the dynamic global vegetation model LPJmL [20]. This data serves as input to the AGRO-module where it is used for suitability assessment and to define the amount of crop production that can be allocated to each cell.

Further input data for the AGRO-module is provided on country level. It comprises scenario data that describes the amount of crop production and crop yield improvements due to technological change (TC). The latter information is used to adjust the crop yields generated by the productivity-module, accordingly. The rational of the AGRO-module is to simulate changes of cropland area in each country of the EU by distributing the crop production to the most suitable raster cells. The algorithm determines the suitability of each grid cell for crop cultivation with a multi-criteria analysis, considering the parameters potential crop yield, terrain slope, population density and road infrastructure. Furthermore, nature conservation areas as well as urban areas are excluded from being converted into cropland. The spatial allocation of crop production is computed with a modified version of the Multi Objective Land Allocation (MOLA) algorithm [14,21]. First, the production of each crop is distributed to the most suitable raster cells with already existing cropland area, and their state variable “dominant land-use type” is set to the respective crop type. If not all of the crop production can be allocated on the existing cropland area, additional suitable land is converted to cropland. Model output is a series of raster maps displaying the change of cropland area during the simulation period.

2.3 Validation of the land-use model

The validation of the AGRO sub-module of LandSHIFT for the European Union considers the ability of the model to simulate quantity and location of cropland area. Validation regarding quantity is done by comparing simulated cropland area for the year 2005 with census data from the FAO [22]. The validation procedure for location is testing the plausibility of the model assumptions about the suitability for cropland. This is achieved by analyzing the statistical distribution of calculated cell suitability values in the initial land-use map with a relative operating characteristic (ROC) [23].

In Fig. 1 census data from FAO [22] is plotted against simulated data from the LandSHIFT model, in order to perform a visual validation. Each data point represents the simulated and "observed" cropland area in 10^6 ha for an EU Member State in 2005. The diagonal black line indicates the position of the perfect fit because along that line observed and simulated data are equal. The vertical deviation from the perfect fit line represents the goodness of fit [24], which describes the discrepancy between observed and simulated data. Fig. 1 shows a strong positive relationship between observed and simulated data along the line of perfect fit. Most values are located in the lower range with relatively small deviations from that line. For larger countries (Romania, Germany, Spain, Poland) there is a trend of underestimating cropland area compared to observed data, which induces higher pressure for LUC in the LandSHIFT model than in reality. Taken together, we conclude from the visual validation that our model is capable to reproduce the observed quantity of cropland area for smaller countries but tends to underestimate cropland area in larger countries.

Figure 1

Additionally, as a statistical test method, the modelling efficiency (ME)[5] [25] is calculated as performance measure. The ME as defined in equation 2 [24] is a dimensionless test statistic which directly relates simulated to observed data by calculating the goodness of fit towards the perfect fit line [26]. While a near perfect model would achieve values close to 1, models with negative values cannot be recommended [24].

(2)

The calculation of the ME is based on the same data employed for the visual validation. For the year 2005 the ME is 0.85. This result indicates that the model output largely matches with the FAO census data and supports the findings from the visual validation. Therefore, we are confident that LandSHIFT's AGRO sub-module is suitable for the simulation of LUC in terms of quantity of cropland use, with limitations for larger countries.

ROC is a tool for the evaluation of LandSHIFT's ability to determine the location of cropland. In our case it relates the proportions of predictions classified as correct and incorrect over the range of suitability classes. For this purpose the calculated suitability values are grouped into 20 classes. In the first step, the frequency distributions of suitability values for cropland and non-cropland cells in the initial land-use map are calculated. This analysis shows that cropland cells have in tendency higher suitability values (0.71) than no-cropland cells (0.44) which gives a first indication that LandSHIFT is capable to simulate the correct location of cropland. Based on the frequency distributions, in the second step the ROC analysis is conducted. Starting with the highest suitability class the proportions of cropland cells (correct predictions) and non-cropland cells (incorrect predictions) are plotted against each other. Performance measure is the area under curve (AUC) which is calculated with the trapezoidal

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[5] The modelling efficiency (ME) is equivalent with the Nash-Sutcliffe model efficiency coefficient.

approximation shown in equation 3 where x_i / y_i is the cumulative non-cropland / cropland frequency for suitability class i and n the number of suitability classes (based on [23]):

(3)

AUC values range between 0 and 1, with 1 marking a perfect allocation. If the suitability values were located randomly across the map, the expected value of the ROC would be 0.5 meaning that the proportion of cropland cells in the different suitability classes would be more or less the same. The calculated AUC of 0.88 is better than this random value, indicating that cropland cells of the initial map can be found predominantly at locations with “high” suitability values.

In summary, we have demonstrated that the employed version of LandSHIFT is a suitable model for the simulation of quantity and location of cropland area.

2.4 Study design

The study area comprises the EU-27 Member States except Malta, Cyprus and Luxembourg which have been excluded because the 5 arc minutes resolution we use is too coarse to allow for analysis of LUC within those countries. When in the following we talk about the EU-27 we always refer to the definition of the study area given above. Our analysis uses scenarios of 1st gen. biofuel production and compares them to a baseline scenario describing a development without biofuels. According to Alcamo [27] we define a scenario as “a description of how the future may unfold based on 'if-then' propositions and typically consists of a representation of an initial situation and a description of the key driving forces and changes that lead to a particular future state”. The scenarios used in our study are derived from the Sustainability Eventually

(SUE) scenario which has been developed within the EU SCENES project[6]. SUE "is a scenario that sketches the transition from a globalizing, market-oriented Europe to environmental sustainability" [29]. It is assumed that exports of agricultural goods to the world markets are substantially reduced. Nevertheless, an increasing crop productivity leads to a decrease of cropland and grazing land. Land use changes in general promote greater biological diversity. The SUE input data for LandSHIFT comprise country-specific information regarding crop production and Technological Change (TC) for each time-step of the simulation period (see below). This data, including imports and exports of agricultural goods, were calculated by the integrated ecological, economic, and socio-demographical policy model AEZ–BLS [30]. It combines the spatially explicit agro-ecological zone model (AEZ) and a regionalized general equilibrium model of world food economy (BLS). Neither 1st nor 2nd gen. biofuels are considered in the SUE scenario. In the framework of our study, the SUE scenario is chosen as baseline scenario in order to serve as reference of comparison for the biofuel scenarios. In the biofuel scenarios total biomass demand increases due to 1st gen. biofuel demand in addition to the baseline's food demand. Since the demand for 1st gen. biofuels is the sole difference between the baseline and biofuel scenarios, it is possible to isolate the impact of 1st gen. biofuel production on land-use change and related GHG emissions..

The biofuel demand is derived from the NREAPs [12] each Member State of the EU had to submit to the European Commission as a consequence of the RED [1]. The NREAPs comprise Member State specific information for the period 2005-2020 on bioethanol and biodiesel usage. Accordingly, the simulation period of our analysis covers the years 2005-2020. The biofuel demand in our study has two restrictions. First of all, we excluded imported biofuels. This implies that potential GHG emissions from LUC of imported biofuels are not accounted for with respect

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[6] SCENES was a research project (2006-2010) under the EU 6th framework program dedicated to the development of future scenarios for Europe's freshwater availability [28]

to the GHG balance of biofuels in the EU Member States. Secondly, we exclusively considered 1st gen. / conventional biofuels and excluded 2nd gen. / advanced biofuels. Up to date, 2nd gen. biofuels are still under development and not yet applied in large-scale [31]. Moreover, we excluded trade of 1st gen. biofuels within the EU.

We developed two biofuel scenarios in order to perform a sensitivity analysis for the production of 1st gen. biofuels in the EU-27. The biofuel demand for each EU Member State considered in the first biofuel scenario, denoted as 1xNREAP, is derived directly from the NREAPs. In the second biofuel scenario, 2xNREAP, the biofuel demand for 2020 is doubled compared to 1xNREAP. Table 1 shows the domestic 1st gen. biofuel demand in 2005 and 2020 on aggregate EU-level taken from NREAPs [12]. In the 1xNREAP scenario 1st gen. biofuel demand in 2020 amounts to 660 PJ, which represents ~5% of aggregate energy consumption in transport in the EU in 2020[7]. Under 2xNREAP this proportion increases to ~10%.

Table 1

In order to process the scenario specific biofuel demands with LandSHIFT, two transformations are necessary. The biofuel demands have to be divided up into the crop types LandSHIFT accounts for and the demand's unit has to be transformed from PJ biofuel into Mt feedstock for each country. Table 2 shows the EU-27 1st gen. biofuel production characteristics in 2010 for the following biofuel production pathways: Bioethanol from wheat, maize, sugar beet and rye / barely; Biodiesel from rapeseed, soybean and sunflower oil. We used the feedstock share as a proxy for the allocation of 1st gen. biofuel demand to different crop types. Based on the EU-level feedstock share in 2010 [32,33], we derived individual bioethanol and biodiesel

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[7] The aggregate energy consumption in transport in the EU in 2020 amounts to 12,927 PJ [12]

feedstock shares for each EU-27 Member State considered in our study[8]. Referring to FAPRI [32], we assume the feedstock shares to be fixed until 2020. The resulting amount of bioethanol and biodiesel [PJ] to be produced from the crop types listed in Table 2 is finally converted into Mt by application of heating value [MJ liter^{-1}] and biofuel yield [liter t^{-1}] [34–37].

Table 2

Table 3 summarizes the aggregate EU-level input data employed in the LandSHIFT model for the starting year (2005) and the final year (2020) of the simulation. Biomass demand for food are taken from the SUE scenario [28]. Biomass demand for 1st gen. biofuel production is derived from the NREAPs [12]. In 1xNREAP biomass demand for 1st gen. biofuel production makes up about one-fifth of total biomass demand in 2020.

Table 3

In order to obtain a range of results from scenario analysis and not just a single value, the baseline as well as the biofuel scenarios are each simulated with technological change (TC) and without (NO-TC). TC is leading to an increase of crop yields by 9.4% between 2005 and 2020 in both, baseline and biofuel scenarios. It is assumed that in the biofuel scenarios TC additionally decreases the GHG emissions from cultivation, processing and transportation by 10% in the whole simulation period[9] (Table 4).

Table 4

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[8] See country specific list of feedstock shares in SI

[9] The resulting average GHG emission saving (equation 5) according to the considered biofuel production pathways is consistent with the IEA Biofuel Roadmap target for 2020 [8]

2.5 GHG emissions from LUC

LUC within the simulation period is determined by analyzing LandSHIFT's scenario specific grid maps for 2005 and 2020 with GIS software. LUC occurs if the land-use type of a cell in 2020 is different from the land-use type of this cell in 2005. The land-use type of a cell changes if the dominant land-use of this cell changes. For instance a grassland cell is converted to cropland if the model starts to grow crops on that cell. The land supporting 1st gen. biofuels and food crops is classified as cropland. Accordingly, the GIS analysis accounts for changes between the land-use types perennial crops, grassland, forest, shrub-lands, set aside land and cropland. The calculation of GHG emissions from LUC (e_l) needed for the LCA described in sub-section 2.1 is defined as shown in equation 4 [1][10]

(4)

where

e_l = annualized emissions from carbon stock change due to LUC [$gCO_{2eq}\ MJ^{-1}$]
CS_R = carbon stock in soil and vegetation associated with reference land use [$tC\ ha^{-1}$]
CS_A = carbon stock in soil and vegetation associated with actual land use [$tC\ ha^{-1}$]
3.664 = factor for the conversion of C to CO_2
20 = annualizing of carbon stock changes over a 20 year period
P = feedstock productivity [$MJ\ ha^{-1}\ a^{-1}$]

In the framework of our study CS_R is the carbon stock in 2005, while CS_A represents the carbon stock in 2020. The calculation takes into account the carbon stocks in soil and vegetation. Since the area for which a carbon stock is calculated shall have similar conditions in terms of land-use, soil and climate, CS_R and CS_A are determined for each cell of the corresponding grid map separately. Cell-level information regarding soil and climate is retrieved from the *JRC Support to Renewable Energy Directive* project [38]. The *guidelines for the calculation of land carbon stocks*

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[10] In the framework of this study it is assumed that no severely degraded or heavily contaminated land is recultivated. Therefore the bonus e_B has been excluded from the equation.

[39] provide land-use, soil and climate type dependent default values for soil organic carbon and vegetation carbon stocks (above and below ground). The calculation of carbon stocks for mineral soils and organic soils is consistent with the IPCC Tier 1 methodology[11]. After the carbon stocks for 2005 and 2020 have been determined , for each cell the annualized GHG emissions from LUC (e_l) are computed according to equation 4. To obtain the change in carbon stocks due to LUC in the simulation period, CS_A is subtracted from CS_R. Then, as explained in Annex V C(7) of the aforementioned guidelines [39], the yearly emissions related to these carbon stock changes are calculated for a time frame of 20 years by allocating it in 20 equal parts to each year. This is due to the fact that some emissions occur during the conversion process itself and others over a long period of time after the conversion [5].

The division of carbon stock changes by the feedstock productivity (P) relates the CO_2 emissions to the energy content (MJ) of biofuels. The country specific P values, representing the energy productivity of feedstock (how much biofuel can be produced per unit area), are derived from Biograce [41] according to the bioethanol / biodiesel ratio of the respective Member State. For EU-level we calculated a feedstock productivity of 53 GJ ha^{-1} a^{-1}.

2.6 Impact Assessment

The impact assessment of GHG emissions from LUC is split up into two steps. At first, the GHG emissions of the biofuel scenarios are related to the GHG emissions of the respective baseline scenario in order to isolate the GHG emissions from LUC caused by 1st gen. biofuel production. Secondly, the GHG emission saving of 1st gen. biofuel use compared to fossil fuel use is calculated based on the LCA result.

In order to isolate the GHG emissions from LUC due to 1st gen. biofuel production from the GHG emissions resulting from LUC due to food production, the baseline scenario GHG

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[11] See [40] for more information on IPCC Tier 1, 2 and 3 methodologies

emissions have to be subtracted from the biofuel scenario GHG emissions. For this purpose the GHG emissions in the baseline and biofuel scenarios have to be presented in the same units. Since in the baseline scenario no biofuel production takes place, its GHG emissions cannot be related to the energy content of biofuels as shown in equation 4. Therefore P^{-1} is not applied until the GHG emissions from LUC due to 1st gen. biofuel production have been isolated. The result (e_l) represents the GHG emissions from LUC caused by the production of 1st gen. biofuels in the simulation period 2005-2020, which is integrated as an elementary flow into the LCA of biofuels [equation 1].

In order to provide an indicator for the GHG performance of biofuels, the GHG emission saving from 1st gen. biofuel compared to fossil fuel use is calculated as shown in equation 5 [1].

$$\frac{-}{\qquad\qquad} \tag{5}$$

where

E_F = total emissions from fossil fuel use [83.8 $gCO_{2eq}\ MJ^{-1}$]
E_B = total emissions from biofuel use [$gCO_{2eq}\ MJ^{-1}$]
AF = allocation factor

E_F, the total emissions attributable to fossil fuel use of 83.8 $gCO_{2eq}\ MJ^{-1}$, is taken from the RED [1] and serves as a comparator for the emissions from biofuel use. E_B, the total emissions from biofuel use, is a direct result of the LCA according to equation 1. The allocation factor (AF) describes the share of emissions attributable to biofuel use. AF is based on Biograce [41] and the biofuel production pathways considered in our study. On EU-level[12] we use an average AF of ~0.59, i.e. ~59 % of energy crops are used for biofuel production, while the remainder is used for co-products (e.g. sugar beet pulp) [42]. The GHG emissions saving from biofuel use is expressed in percent of saved GHG emissions compared to fossil fuel use and is directly

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[12] See result tables in SI for Member State figures

comparable to the minimum saving target of 35% laid down in the RED, which is mandatory for all Member States [1].

3. Results

3.1 LUC and related GHG emissions on EU-level

Table 5 summarizes the results from analyzing LandSHIFT grid maps with GIS software concerning LUC and GHG emission from LUC for the period 2005-2020 on aggregate EU-level. As pointed out in sub-section 2.5, land-use changes comprise conversions of non-cropland to cropland as well as from cropland to non-cropland / set aside land. In the baseline scenario with technological change (TC) total LUC amounts to 15 x 10^6 ha, while the annualized GHG emissions from LUC related to that area amount to -29 $MtCO_{2eq}$ a^{-1}. Negative GHG emissions represent net carbon sinks and can therefore be interpreted as GHG emission savings. These negative GHG emissions from LUC occur because food demand in the baseline scenario increases by ~1 %, while crop productivity due to TC increases by ~10 % [Tables 3, 4]. This causes the conversion of cropland to set-aside land. Accordingly total cropland area decreases from 90 x 10^6 ha in 2005 to 84 x 10^6 ha in 2020. Due to ecological succession on the new set-aside land, carbon dioxide is detracted from the atmosphere. In the baseline under NO-TC total LUC in the study area amounts to 10 x 10^6 ha, while the GHG emissions from LUC amount to 2 $MtCO_{2eq}$ a^{-1}. GHG emissions from LUC in the baseline under NO-TC are positive because the missing TC requires the conversion of non-cropland to cropland in order to fulfill the demand for food crops, leading to an slight increase of cropland area by 2020.

In the biofuel scenarios LUC and the related GHG emissions are increasing. In 1xNREAP total LUC between 2005 and 2020 amounts to 19 x 10^6 ha under TC and to 22 x 10^6 ha under

NO-TC with cropland area increasing to 100 x 10^6 ha and 106 x 10^6 ha respectively by 2020. In 2xNREAP total LUC for the study area in the simulation period amounts to 30 x 10^6 ha under TC and to 35 x 10^6 ha under NO-TC[13]. Cropland area is increasing to 111 x 10^6 ha (TC) and 112 x 10^6 ha (NO-TC) by 2020. Based on the initial cropland area in 2005 (90 x 10^6 ha) and the total cropland area in the biofuel scenarios by 2020 we derive land requirements for 1st gen. biofuel production ranging from 10 - 16 x 10^6 ha in 1xNREAP and from 11 - 22 x 10^6 ha in 2xNREAP, which is in the same order of magnitude as the figures published by RFA [9].

Under all NO-TC scenarios LUC figures are larger than the corresponding LUC figures under TC due to the missing increase in crop yields. Under TC the aggregate GHG emissions from LUC for all Member States amount to 68 $MtCO_{2eq}\ a^{-1}$ in 1xNREAP and to more than twice of that, 143 $MtCO_{2eq}\ a^{-1}$, in 2xNREAP. To recap, GHG emissions from LUC in the biofuel scenarios are caused by food *and* biofuel production. Since the biofuel production in 2xNREAP is doubled compared to 1xNREAP this represents a positive scale effect regarding GHG emissions from LUC under TC. Under NO-TC the aggregate GHG emissions from LUC for all Member States amount to 98 $MtCO_{2eq}\ a^{-1}$ in 1xNREAP and to 186 $MtCO_{2eq}\ a^{-1}$ in 2xNREAP, which represents a negative scale effect[14]. In general, the non-linearity between biofuel production and GHG emissions from LUC can be explained by disproportionally increasing demands for cropland. The demand for cropland does not grow proportionally with the biofuel production because additionally cultivated land can hold different crop yields and because TC affects the demand for cropland.

The quotient of total GHG emissions and total LUC area [Table 5, columns 1-2] returns per hectare GHG emissions [Table 5, column 3] in $tCO_{2eq}\ ha^{-1}\ a^{-1}$. In the baseline scenario under TC annual per-hectare GHG emissions due to food *and* biofuel production amount to -2.0 $tCO_{2eq}\ ha^{-}$

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[13] See result tables in SI for Member State figures

[14] See result tables in SI for Member State figures

^{1} a^{-1}, while under NO-TC emissions are positive with 0.2 tCO$_{2eq}$ ha^{-1} a^{-1}. In the biofuel scenarios per hectare GHG emissions increase and range between 3.5 - 4.4 tCO$_{2eq}$ ha^{-1} a^{-1} in 1xNREAP and 4.7 - 5.3 tCO$_{2eq}$ ha^{-1} a^{-1} in 2xNREAP. All results described up to here represent GHG emissions from LUC caused by food *and* biofuel production. In order to carry out a LCA of biofuels the GHG emissions from LUC due to biofuel production are isolated by subtracting the baseline scenario emissions from the biofuel scenario emissions [see sub-section 2.6]. For 1xNREAP this results in GHG emissions from LUC attributable to 1st gen. biofuel production of 4.1 (no-TC) and 5.5 (TC) tCO$_{2eq}$ ha^{-1} a^{-1}, while for 2xNREAP GHG emissions from LUC attributable to 1st gen. biofuel production range between 5.1 (NO-TC) and 6.7 (TC) tCO$_{2eq}$ ha^{-1} a^{-1}.

Table 5

3.2 GHG emissions from LUC on Member State level

Fig. 2 shows the annual GHG emissions [tCO$_{2eq}$ ha^{-1} a^{-1}] from LUC due to 1st gen. biofuel production on cell-level. The annual per-hectare GHG emissions represent changes in GHG emissions, i.e. the difference between GHG emissions from LUC in the 1xNREAP and the baseline scenario under TC for the period 2005-2020. In the legend of Fig. 2 these changes in GHG emissions are classified in five groups: Negative GHG emissions, i.e. carbon stock increases due to LUC, are indicated by green color. Cells with no change in GHG emissions, i.e. no LUC takes place, are colored in white. Positive GHG emissions are indicated by pastel (low, 0 - 5 tCO$_{2eq}$ ha^{-1} a^{-1}), orange (medium, 5 - 10 tCO$_{2eq}$ ha^{-1} a^{-1}) and red (high, > 10 tCO$_{2eq}$ ha^{-1} a^{-1}).

Fig. 2

The map in Fig. 2 reveals that only in about 6% of all cells simulated (~80,000) LUC and related GHG emissions attributable to 1st gen. biofuel production occur, while all other cells show up in white indicating no change in GHG emissions compared to the baseline scenario. In about 5% of all cells GHG emissions are positive, while in about 1% of all cells negative GHG emissions can be observed. Most negative GHG emissions occur in Germany, Spain, France, Poland and Italy. LUC in these cells primarily consists of conversions from cropland to set-aside land. Due to ecological succession on set-aside land additional carbon dioxide is detracted from the atmosphere and stored in above- and belowground carbon stocks. Denmark, Romania and Greece show zero GHG emissions attributable to 1st gen. biofuel production. In Denmark and Romania no biofuel is produced at all[15], while in Greece the transport sector share, the proportion of renewable energy in the whole transport sector, amounts to 3%. Low GHG emissions due to biofuel production (0 - 5 tCO_{2eq} ha^{-1} a^{-1}) mainly occur in Poland, France, Spain, Hungary and Bulgaria, while medium GHG emissions due to biofuel production (5 - 10 tCO_{2eq} ha^{-1} a^{-1}) mainly occur in the Benelux and Baltic states, Southern Italy, Ireland, Spain, France and in some spots in Scandinavia. Low and medium GHG emission are primarily caused by the conversion of perennial crops, grassland and set-aside land to cropland. In Finland GHG emissions are triggered by the conversion of shrublands on organic soils to cropland. High GHG emissions (> 10 tCO_{2eq} ha^{-1} a^{-1}) occur primarily in Slovenia, which shows up almost completely in red, and in some spots in Portugal, France, Italy, Germany, Poland and the Baltic States. These are primarily caused by the conversions of forest to cropland. It has to be noted that the transport sector share of Slovenia is high and amounts to 10%.

Taken together, the GHG emissions from LUC depend on the type of land conversion, for example from grassland to cropland or from forest to cropland, and the climate and soil type. Under NO-TC GHG emissions from LUC are in general higher, but the national differences

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[15] See result tables in SI for detailed Member State figures

remain similar. In 2xNREAP GHG emissions from LUC increase, especially in countries with relatively low GHG emissions from LUC in 1xNREAP.

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3.3 Impact assessment

LCA of biofuels and GHG performance on EU-level

Table 6 shows the LCA of 1st gen. biofuels in terms of gCO_{2eq} MJ^{-1} for the whole study area in the period 2005 - 2020 on aggregate EU-level as well as the GHG emission saving indicator. The GHG emissions from LUC (e_l) for the LCA are obtained by multiplying the isolated GHG emissions from LUC due to biofuel production [Table 5, column 4] with the factor P^{-1} [53 GJ ha^{-1} a^{-1} on EU-level, see sub-section 2.5]. Together with the GHG emissions from cultivation (e_{ec}), processing (e_p) and transport (e_{td}), they represent the total GHG emissions from biofuel production (E_B). Allocated E_B is being obtained by applying the allocation factor to E_B [59% on EU-level, see sub-section 2.1]. The GHG emission saving indicator is calculated by relating allocated E_B to the GHG emissions from fossil fuel use [sub-section 2.6]. The GHG emission savings of biofuel compared to fossil fuel use range between -2% (TC) and 13% (NO-TC) in 1xNREAP and between -18% (TC) and 1% (NO-TC) in 2xNREAP. Since negative emission savings equal positive emissions the use of biofuels in 1xNREAP and 2xNREAP under TC emits more GHG's than the use of fossil fuels. The mandatory GHG emission saving target laid down in the RED of 35% [1] is not reached under any 1st gen. biofuel scenario on aggregate EU-level.

Table 6.

GHG performance on Member State level

To highlight the national differences in the GHG performance of biofuels, Fig. 3 shows the GHG emission saving indicator in 1xNREAP under TC and NO-TC for the period 2005-2020 on

Member State level. The vertical line represents the mandatory 35% GHG emission saving target laid down in the RED [1]. In 1xNREAP the five Member States Bulgaria, Germany, Greece, Latvia and Great Britain achieve this target under TC, NO-TC or both. Italy and Bulgaria reach the 35% target under NO-TC but have positive GHG emissions under TC. The remaining Member States feature GHG emission savings below 35%, while the GHG emission savings are at least positive in France, Hungary, Poland, Slovakia and Spain. In Austria, Estonia, Finland, Slovenia and Sweden GHG emissions from 1st gen. biofuel use are higher compared to fossil fuel use. However, the transport sector share[16] of countries reaching the 35% target is relatively low compared to countries with GHG emission savings below that target [see SI].

At first glance it seems not intuitive that with technological change GHG emissions from 1st gen. biofuel use can be higher than without (e.g. Ireland, Italy, Portugal). The effect can be explained by taking into account the carbon stock changes in the baseline scenario. In the baseline with TC less cropland is needed to fulfill the biomass demand due to higher increase in crop yields [Table 3-4]. The leftover cropland is converted to set-aside land. Ecological succession takes place and detracts carbon from the atmosphere. This results in negative GHG emissions in the baseline under TC while GHG emissions are positive in the baseline under NO-TC. In the biofuel scenarios overall GHG emissions increase. The GHG emissions attributable to 1st biofuel production are represented by the difference of the corresponding biofuel scenario and baseline scenario carbon stocks. Since GHG emissions in the baseline under TC are negative, the impact of 1st gen. biofuel production on the GHG emission saving indicator is higher under TC than NO-TC.

Fig. 3

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[16] See result tables in SI for detailed Member State figures

4. Discussion

In this study, we coupled a spatial model for the simulation of LUC to a LCA of biofuels in order to determine the impact of GHG emissions from LUC on the overall GHG performance of biofuels. Geyer et al. [4] applied a similar approach for biodiversity assessments of LUC in California. Compared to this our study for the Member States of the EU can be considered as a large-scale analysis. Since geospatial information about land-use is necessary for the precise calculation of carbon stocks in soil and vegetation, we estimated LUC for each cell of a 5 arc minutes grid map of the study area. This spatial resolution allows analyzing the impacts of general land-use dynamics at the national and the European level. It is not suitable to capture land-use change that operates on local or regional level for example due to changes of farming practices. Finally, the obtained GHG emissions from LUC for each cell have been aggregated to country or EU-level and transferred, as an elementary flow, to the LCA of biofuels.

For the determination of LUC we used the spatially explicit simulation model LandSHIFT. Since LandSHIFT represents a demand driven approach it is capable to take into account competition for land resources between food and biofuel production. The LandSHIFT model was validated for our study area, the EU-27 except Malta, Cyprus and Luxembourg, in terms of quantity and location of cropland use. Quantity of cropland use was validated visually and by calculating the modeling efficiency (ME). Validation of location of cropland use was done by performing a relative operating characteristic (ROC) and calculating the area under the curve (AUC) as performance measure for LandSHIFT's suitability evaluation. Both performance measures indicate that the employed model can be considered as suitable for the simulation of LUC. For larger countries (Romania, Germany, Spain, Poland) it has to be taken into account that LandSHIFT tends to underestimate the cropland area, leading to increasing pressure for LUC.

Our analysis uses scenarios of 1st gen. biofuel production and compares them to a baseline scenario describing a development pathway without biofuels. As each scenario is run with and without technological change (TC) the biofuel scenarios could be compared to multiple baselines. In the baseline scenarios, biomass demand is driven by food demand alone, while in the biofuel scenarios biomass demand increases due to additional biomass demand for 1st gen. biofuels. First of all, this setup made it possible to capture the whole impacts of 1st gen. biofuel production on the land system in terms of GHG emissions. Secondly, by examining the sensitivity of GHG emissions from both traditional agronomy and biofuel production as the systems develop with improved efficiency (TC) the idea that 1st gen. biofuel production will reduce GHG emissions can be challenged. Taken together, these issues demonstrate the importance of LUC in GHG emissions associated with 1st. gen biofuel production. Since the results obtained from our analysis strongly depend on the baseline scenario LUC GHG emissions, we clearly have to highlight that a change of the baseline scenario setup can lead to fundamental different results. Figures for the biofuel production in the biofuel scenarios were derived from the NREAPs [12] and thus are based on assumptions of the Member States regarding their biofuel consumption in the period 2005-2020. Moreover, the applied methodology of carbon stock calculation in the GIS software is consistent with the *guidelines for the calculation of land carbon stocks* provided by the European Commission [39] and the employed LCA approach, a well-to-wheels analysis, is consistent with the LCA methodology described in the RED [1]. The GHG emissions calculated for the 1xNREAP scenario (68 $MtCO_{2eq}$ a^{-1}) lie within the range of GHG emissions from LUC estimated from Bowyer and colleagues [11] which is between 44 and 77 $MtCO_{2eq}$ a^{-1} on EU-level.

By coupling the spatial model to the LCA of biofuels we identified the relationship between 1st gen. biofuel production and GHG emissions to be not linear. This is an important finding with respect to LCA because it contradicts the assumption that a doubling of biofuel production generates twice as much GHG emissions from LUC. Moreover, we showed that LUC has a major impact on the GHG performance of biofuels. Without taking LUC into account in the LCA, the average GHG emission saving compared to fossil fuel use amounts to about 50%[17]. In this case the mandatory 35% GHG emission saving target of the RED would be fulfilled. If LUC is considered in the LCA of biofuels the average GHG emission saving on EU-level ranges between -2% and 13% under 1xNREAP. Thus the 35% target is not reached under 1xNREAP. Under 2xNREAP, in which the biofuel demand is doubled compared to 1xNREAP, the GHG emission saving becomes negative and ranges between -18% and 1%. Since we excluded imported and 2nd gen. biofuels in our analysis, the transport sector share of biofuels in 1xNREAP in 2020 amounts not to 10%, the mandatory target of the RED, but to 5.1%. Instead, under 2xNREAP a transport sector share of 10% is reached by the domestic production of 1st gen. biofuels. Since GHG emission savings under 2xNREAP are negative this implies that a production quantity of biofuels compatible with the 10% target emits more GHGs than fossil fuel use.

According to our results on EU-level 1st gen. biofuel use does not substantially reduce GHG emissions compared to fossil fuel use. Depending on the conditions biofuel use can be even less attractive than fossil fuel use. Our results question the EU biofuel policy because the introduction of biofuel quotas is aimed to mitigate global warming. If 1st gen. biofuel use does not substantially reduce GHG emissions compared to fossil fuel use, it cannot be considered as an adequate measure for the mitigation of global warming.

However, there are huge national differences. Germany, Greece and Great Britain for instance reach the 35% target, while Slovenia emits 70-100% more GHGs when using biofuels instead of fossil fuels. In Germany, although LandSHIFT underestimates the initial cropland area,

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[17] Calculated using equation 5 (without allocation) and average GHG emission values for cultivation, processing, and transport and distribution for the biofuel production pathways considered in this study [1].

there is enough cropland available to fulfill the biomass demand for 1st gen. biofuel production derived from the NREAPs. Therefore cropland is converted to set aside land, where the ecological succession detracts carbon from the atmosphere. Since Greece and Great Britain anticipate to import most of their 1st gen. biofuels the pressure for LUC is relatively low in these countries. In Slovenia the cropland needed to fulfill the biofuel demand is mainly obtained by the conversion of forest to cropland. Due to this LUCs the carbon stored in soil and vegetation of the forest, which is more than in most other land-use types, is released to the atmosphere. This process results in the highest GHG emissions from LUC obtained from our analysis. If Slovenia would realize its 1st gen. biofuel production as stated in their NREAP, almost the whole forest area would be threatened. Both Poland and Spain appear to fail to reach the target, despite having reduced GHG emissions; the underestimation of initial agronomic area in LandSHIFT may be the cause.

The seven EU Member States reaching the 35% GHG emission saving target have generally smaller transport sector requirements than those failing, a consequence of a proportional target. Since each Member State has to cover 10% of the energy consumption in transport by renewable sources in 2020 a low transport sector share indicates a high import quota of biofuels. The impact of imported biofuels on the overall GHG performance of biofuels was not assessed in this study which limits the significance of the GHG emission saving indicator. Hence,our calculations can be interpreted as rather optimistic estimate because the consideration of imported biofuels in the LCA is likely to increase GHG emissions due to land-use changes in exporting regions [43]. In these scenarios, on average the EU-27 Member States anticipate to import 29% of all biofuels in 2020 [12]. In addition, 2nd gen. biofuels, which represent a proportion of 19% in terms of total biofuels in 2020 [12] as well as trade of 1st gen. biofuel within the EU were not considered. A comprehensive sensitivity analysis that would be necessary to determine the effects of these influencing factors on the GHG balance of biofuels was beyond the scope of this study.

There are several challenges for further research in the field of GHG emissions due to biofuel production. Examples include the reduction of uncertainties in the applied data and system descriptions, the standardization of carbon accounting methods and the better determination of N emissions from fertilizer application [44,45]. In this context particular emphasis should be on the linkage between future yield increases and N_2O emissions resulting from an associated increasing fertilizer use which would have an additional negative effect on the total GHG balance of biofuels [46].

Since different biofuel production pathways entail different environmental impacts, a detailed spatial analysis makes it possible to identify preferable pathways, not only in terms of GHG emissions but also in terms of biodiversity and water needs [44]. Another driver of interest with respect to biofuel production is climate change, which has impacts on crop yields and water availability. Finally, the consideration of imported biofuels, trade patterns, costs and prices could contribute to the assessment of environmental and economic impacts inside *and* outside the EU.

5. Conclusion

If the assumptions made during this exercise are accepted and not compromised, we have demonstrated that under specific constraints LUC has a major impact on GHG emissions, casting doubt on the ability of 1st gen. biofuels to mitigate anthropogenic climate change. Indeed, 1st gen. biofuels may even be more damaging than fossil fuels. Taking our findings along with other critical comments (e.g. UK RFA [9] and IEEP [11]), we conclude that the national 1st gen. biofuel targets for the transport sector of the EU Member States must be reconsidered fundamentally and revised.

Although in their current form 1st gen. EU grown biofuels cannot be considered as an effective measure for the mitigation of global warming by Europe, their value in specific locations, not only for climate change mitigation but also energy security and economic development must be assessed.

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Bibliography

[1] European Parliament and Council. Directive 2009/28/EC of 23 April 2009 on the promotion of the use of energy from renewable sources. OJ L 2009;140:1–52.
[2] Ecofys. Biofuels Baseline 2008. 2011. Available from: http://www.ecofys.com/en/publication/biofuels-baseline-2008/; [accessed 2012 Sep 21].
[3] ISO 14040. Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization (ISO); 1996.
[4] Geyer R, Stoms D, Lindner J, Davis F, Wittstock B. Coupling GIS and LCA for biodiversity assessments of land use. Int J Life Cycle Asscess 2010;15:454–67.
[5] Lange M. The GHG balance of biofuels taking into account land use change. Energ Policy 2011 May;39:2373–85.
[6] Ponti L, Gutierrez AP. Overview on Biofuels From a European Perspective. B Sci Technol Soc 2009 Nov 13;29:493–504.
[7] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. Science 2008 Feb 29;319:1238–40.
[8] IEA. Technology roadmap: Biofuels for transport. International Energy Agency; 2011.
[9] UK RFA. The Gallagher Review of the indirect effects of biofuels production. UK Renewable Fuels Agency; 2008.
[10] Logan TJ, Lal R, Dick WA. Tillage systems and soil properties in North America. Soil and Tillage Research 1991 Jun;20:241–70.
[11] Bowyer C. Anticipated Indirect Land Use Change Associated with Expanded Use of Biofuels and Bioliquids in the EU – An Analysis of the National Renewable Energy Action Plans. Institute for European Environmental Policy (IEEP); 2011. page 1–24.
[12] European Commission. National Renewable Energy Action Plans (NREAPs). 2010. Available from: http://ec.europa.eu/energy/renewables/action_plan_en.htm; [accessed 2012 Sep 19].
[13] DG Energy. The Impact Of Land Use Change On Greenhouse Gas Emissions From Biofuels And Bioliquids. Directorate-General for Energy of the European Commission; 2010. page 5–8.
[14] Schaldach R, Alcamo J, Koch J, Kölking C, Lapola DM, Schüngel J, et al. An integrated

approach to modelling land-use change on continental and global scales. Environ Modell Softw 2011 Aug;26:1041–51.

[15] Schaldach R, Priess JA, Alcamo J. Simulating the impact of biofuel development on country-wide land-use change in India. Biomass Bioenerg 2011 Jun;35:2401–10.

[16] Brinkman N, Wang M, Weber T, Darlington T. Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems - A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions. Argonne National Laboratory; 2005. page 11.

[17] Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C, et al. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. PNAS 2010 Feb 8 [accessed 2013 Feb 18]; Available from: http://www.pnas.org/content/early/2010/02/02/0907318107; [accessed 2013 Feb 18].

[18] Turner BL, Lambin EF, Reenberg A. The emergence of land change science for global environmental change and sustainability. PNAS 2007 Dec 26;104:20666–71.

[19] EEA. Corine land cover 2000. European Environment Agency; 2007. Available from: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-250-m-version-9-2007; [accessed 2011 Jul 15].

[20] Bondeau A, Smith PC, Zaehle S, Schaphoff S, Lucht W, Cramer W, et al. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob Change Biol 2007;13:679–706.

[21] Eastman JR, Jin W, Kyem PAK, Toledano J. Raster Procedures for Multi-Criteria/Multi-Objective Decisions. Photogram. Eng. Remote Sensing 1995 May;61:539–47.

[22] FAO. FAO statistical database. Food and Agriculture Organization of the United Nations; 2011. Available from: http://faostat.fao.org; [accessed 2011 Jul 11].

[23] Pontius Jr. RG, Schneider LC. Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. Agr Ecosyst Environ 2001 Jun;85:239–48.

[24] Mayer DG, Butler DG. Statistical validation. Ecol Model 1993 Jul;68:21–32.

[25] Loague K, Green RE. Statistical and graphical methods for evaluating solute transport models: Overview and application. J. Contam Hydrol 1991 Jan;7:51–73.

[26] Schaldach R, Alcamo J. Coupled simulation of regional land use change and soil carbon sequestration: A case study for the state of Hesse in Germany. Environ Modell Softw 2006 Oct;21:1430–46.

[27] Alcamo J. Environmental Futures: The Practice Of Environmental Scenario Analysis. Amsterdam, Boston: Elsevier; 2008.

[28] CESR. Background Document on Scenarios for the project Climate Adaptation – modelling water scenarios and sectoral impacts. Center for Environmental Systems Research; 2010. Available from: http://www.climwatadapt.eu/scenarios; [accessed 2012 Sep 24].

[29] Kok K, Van Vliet M, Bärlund I, Sendzimir J, Dubel A. First (“First-order”) Draft of Pan-European Storylines—Results from the Second Pan-European Stakeholder Workshop. SCENES Deliverable 2009;2.

[30] Fischer G, Shah M, Tubiello FN, Velhuizen H van. Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Phil. Trans. R. Soc. B 2005 Nov 29;360:2067–83.

[31] Fischer G, Prieler S, Van Velthuizen H, Lensink SM, Londo M, De Wit M. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. Biomass Bioenerg 2010 Feb;34:159–72.

[32] FAPRI. US and World Agricultural Outlook. Food and Agricultural Policy Research Institute; 2010. page 326.

[33] FAS U. EU Annual Biofuels Report. USDA Foreign Agricultural Service; 2010. page 1–38.

[34] FNR. Basisdaten Bioenergie Deutschland. Fachagentur Nachwachsende Rohstoffe e.V.; 2012. Available from: http://mediathek.fnr.de/broschuren/bioenergie/biokraftstoffe/basisdaten-bioenergie.html; [accessed 2012 Sep 26].

[35] Johnston M, Foley JA, Holloway T, Kucharik C, Monfreda C. Resetting global expectations from agricultural biofuels. Environ. Res. Lett. 2009 Jan;4:014004.

[36] European Commission. Impact of the EU biofuel target on agricultural markets and land use. 1st ed. Luxemburg: European Commission; 2011.

[37] Kavalov B. Biofuels potential in the EU. European Commission Joint Research Centre; 2004. page 24.

[38] JRC. Support to Renewable Energy Directive. European Commission Joint Research Centre; 2011. Available from: http://eusoils.jrc.ec.europa.eu/projects/RenewableEnergy; [accessed 2011 Jul 7].

[39] European Commission. Commission Decision of 10 June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC. OJ L 2010;151:19–41.

[40] IPCC. IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change; 2006. page 5.17–5.37. Report No.: Vol. 4.

[41] BioGrace. Biograce Excel Greenhouse gas emission calculation tool. Intelligent Energy Europe Programme; 2012. Available from: http://www.biograce.net/content/ghgcalculationtools/overview; [accessed 2012 Sep 19].

[42] Alberici S, Hamelinck C, Schueler V. Annotated example of a land carbon stock calculation using standard values. ECOFYS; 2010. page 1–14.

[43] Bringezu S, O'Brien M, Schütz H. Beyond biofuels: Assessing global land use for domestic consumption of biomass: A conceptual and empirical contribution to sustainable management of global resources. Land Use Policy 2012 Jan;29:224–32.

[44] McKone TE, Nazaroff WW, Berck P, Auffhammer M, Lipman T, Torn MS, et al. Grand Challenges for Life-Cycle Assessment of Biofuels. Environ. Sci. Technol. 2011 Mar 1;45:1751–6.

[45] Cherubini F, Strømman AH. Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresource Technology 2011 Jan;102:437–51.

[46] Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics Discussions 2007 Aug 1;7:11191–205.

Figure captions

Fig. 1. Validation of LandSHIFT cropland area. Points represent national values of cropland area [10^6 ha] for 2005 as published by the FAO [22] on the vertical axis and as simulated by the LandSHIFT model on the horizontal axis.

Fig. 2. Gridded map of the study area showing changes in annual per hectare CO_2 emissions [tCO_2 ha^{-1} a^{-1}] from LUC due to 1st gen. biofuel production in 1xNREAP compared to the baseline scenario under technological change (TC) for the period 2005-2020.

Fig. 3. GHG emission saving from biofuel use compared to fossil fuel use [%] in 1xNREAP with technological change (TC) and without (NO-TC) for the period 2005-2020. The national GHG emission saving values are evaluated towards the EU target of 35% [1].

Table 1

Table 1. Domestic 1st gen. biofuel demand in 2005 and 2020 on aggregate EU-level taken from NREAPs [11] in PJ

	2005	**2020**
Baseline	0	0
1xNREAP	111	660
2xNREAP	111	1320

Table 2

Table 2. EU-27 1st gen. biofuel production characteristics in 2010

	Bioethanol from				Biodiesel from		
	wheat	maize	sugar beet	rye, barley	rape-seed	soy-bean	sun-flower
Feedstock [Mt] [a]	4.5	2.5	10.9	16	7.0	0.9	0.3
Feedstock share [%]	23%	13%	56%	8%	86%	11%	3%
Biofuel yield [liter t^{-1}] [b]	374	413	102	335	417	199	436
Heating value [MJ $liter^{-1}$] [c]	21.06				32.65		

[a] mean values [34-35]
[b] mean values [36-39]
[c] [36]

Table 3

Table 3. Aggregate EU-level input data employed in the LandSHIFT model for 2005 and 2020

		Biomass	
		Food [Mt]	**Biofuel** [Mt]
2005	Baseline	600	0
	1xNREAP	600	20
	2xNREAP	600	20
2020	Baseline	606	0
	1xNREAP	606	126
	2xNREAP	606	252

Table 4

Table 4. Technological change (TC) scenario assumptions for the simulation period (2005-2020). TC implies an increase of yields of both biofuel and food crops. At the same time GHG emissions in the biofuel industry are reduced.

	Crop yields	**GHG emissions** [a]
TC	9.4%	-10%
NO-TC	0%	0%

[a] GHG emission reduction in biofuel industry

Table 5

Table 5. Estimated average land-use change (LUC) and GHG emissions from LUC in the period 2005-2020 on aggregate EU-level (results from GIS analysis of LandSHIFT grid maps). The first two columns represent total LUC area [10^6 ha] and total GHG emissions from LUC [$MtCO_{2eq}$ a^{-1}] due to food and biofuel production. The quotient of total GHG emissions and total LUC area returns per hectare GHG emissions [tCO_{2eq} ha^{-1} a^{-1}]. The last column shows GHG emissions attributable to biofuel production [tCO_{2eq} ha^{-1} a^{-1}].

		Food & Biofuel production			GHG emissions attributable to biofuel production
		Total LUC area	**Total GHG emissions**	**Per hectare GHG emissions**	
		[10^6 ha]	[$MtCO_{2eq}$ a^{-1}]	[tCO_{2eq} ha^{-1} a^{-1}]	[tCO_{2eq} ha^{-1} a^{-1}]
TC	Baseline	15	-29	-2.0	0
	1xNREAP	19	68	3.5	5.5
	2xNREAP	30	143	4.7	6.7
NO-TC	Baseline	10	2	0.2	0
	1xNREAP	22	98	4.4	4.1
	2xNREAP	35	186	5.3	5.1

Table 6

Table 6. LCA of 1st gen. biofuels for the period 2005-2020 on aggregate EU-level and GHG emission saving indicator

		LCA of biofuels [gCO_{2eq} MJ^{-1}]				**GHG emission saving**[a]
		e_l	e_{ec} + e_p + e_{td}	E_B	Allocated E_B	
TC	1xNREAP	103	41	144	85	-2%
	2xNREAP	126	41	166	99	-18%
NO-TC	1xNREAP	77	45	122	73	13%
	2xNREAP	95	45	140	83	1%

[a] GHG emission saving compared to fossil fuel use (83.8 gCO_{2eq} MJ^{-1})

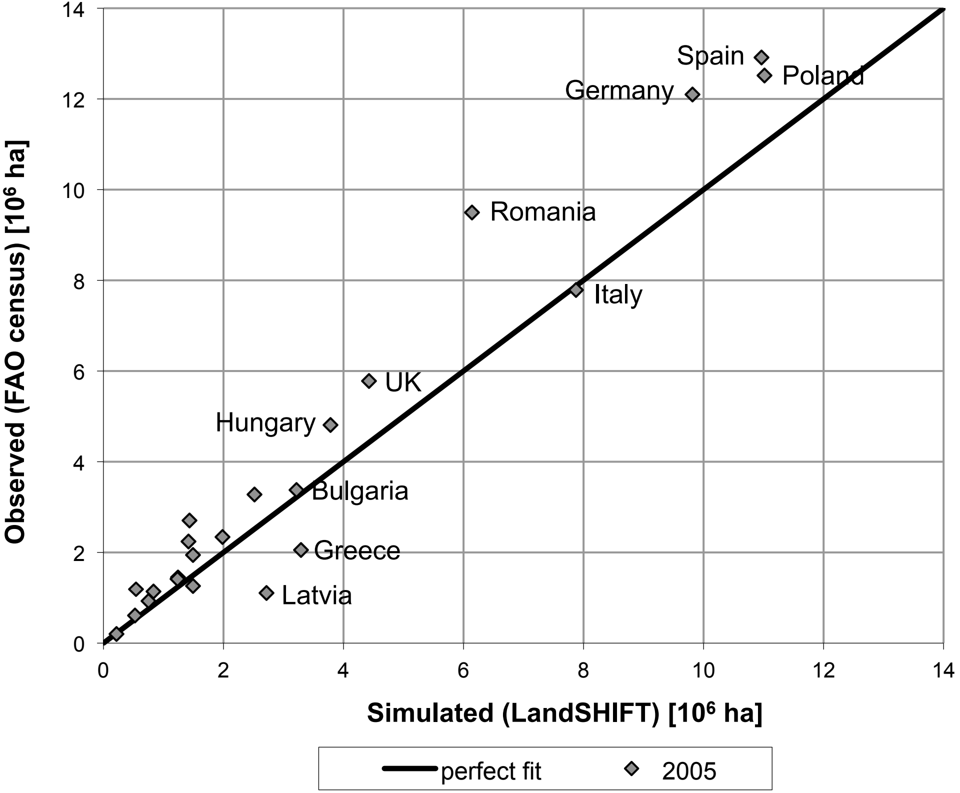
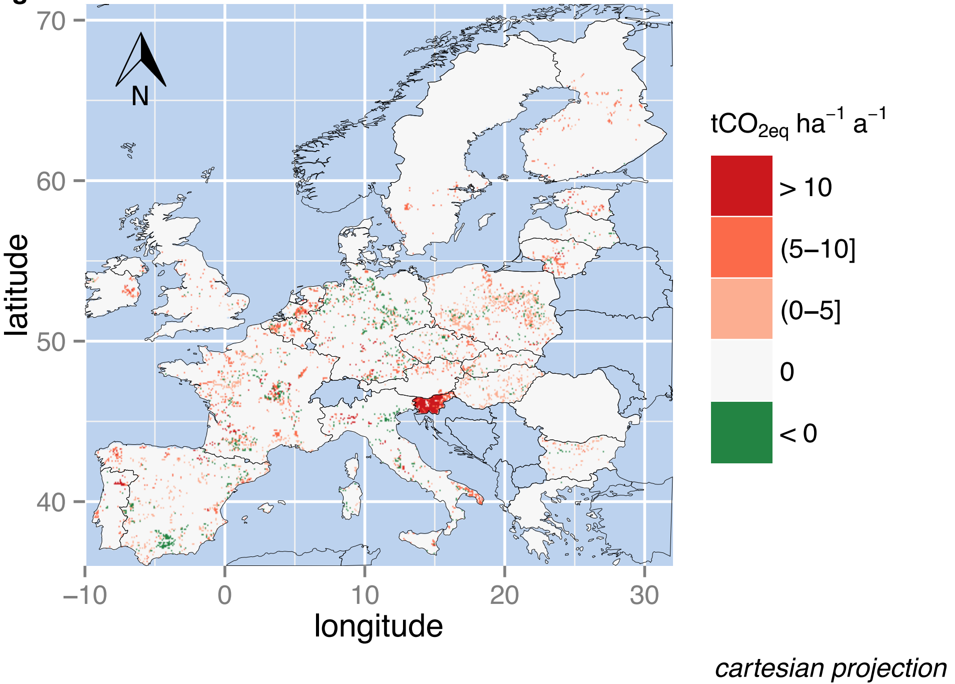
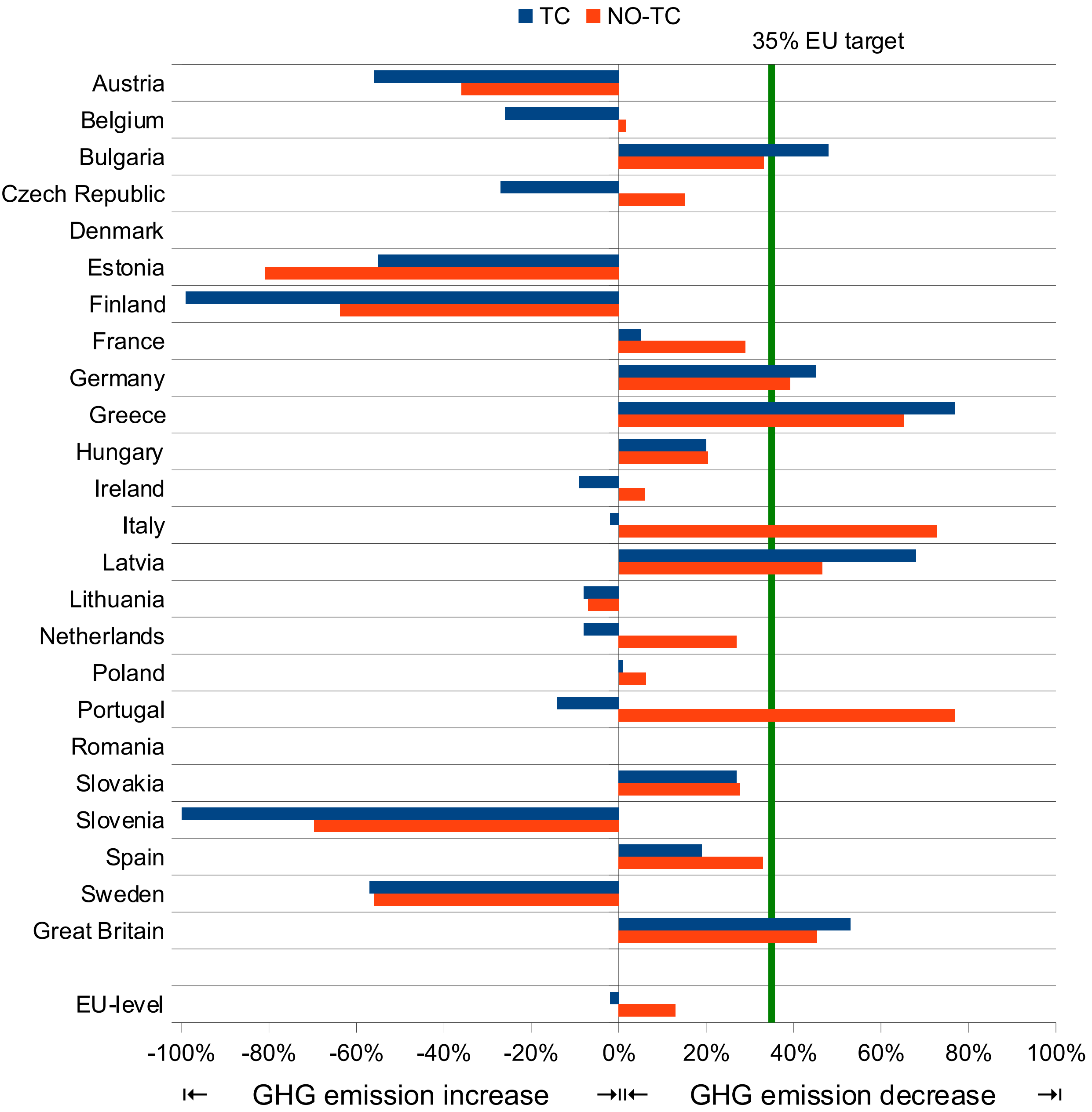

Spain
Poland
Germany
Romania
Italy
UK
Hungary
Bulgaria
Greece
Latvia
0
2
4
6
8
10
12
14
Observed (FAO census) [10^6 ha]
Simulated (LandSHIFT) [10^6 ha]
perfect fit
2005

Figure 2


N
70
60
50
40
latitude
–10
0
10
20
30
longitude
tCO_{2eq} ha^{-1} a^{-1}
> 10
(5–10]
(0–5]
0
< 0
cartesian projection


TC
NO-TC
35% EU target
Austria
Belgium
Bulgaria
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Latvia
Lithuania
Netherlands
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Sweden
Great Britain
EU-level
-100%
-80%
-60%
-40%
-20%
0%
20%
40%
60%
80%
100%
⇤ GHG emission increase →II←
GHG emission decrease ⇥

Assumed feedstock productivity[1] [$GJ\ ha^{-1}\ a^{-1}$]

Bioethanol from				Biodiesel from		
wheat	maize	sugar beet	rye, barley	rape-seed	soy-bean	sun-flower
41	31	153	41	43	18	36

Assumed biofuel feedstock shares, biofuel shares and feedstock productivity

	Bioethanol feedstock shares				Biodiesel feedstock shares			Biofuel shares[2]		Feedstock productivity[3]
ISO	*wheat*	*maize*	*root crops*	*other cereals*	*rapeseed oil*	*soybean oil*	*sunflower oil*	*bioethanol*	*biodiesel*	*$GJ\ ha^{-1}\ a^{-1}$*
AT	23%	13%	56%	8%	86%	11%	3%	23%	77%	54
BE	23%	13%	56%	8%	100%	0%	0%	14%	86%	51
BG	42%	32%	0%	27%	86%	11%	3%	27%	73%	39
CZ	23%	13%	56%	8%	86%	11%	3%	28%	72%	57
DK	27%	0%	60%	12%	100%	0%	0%	0%	0%	0
EE	58%	0%	0%	43%	100%	0%	0%	43%	57%	42
FI	27%	0%	60%	12%	100%	0%	0%	24%	76%	58
FR	23%	13%	56%	8%	92%	0.0%	8%	0%	100%	52
DE	23%	13%	56%	8%	86%	11%	3%	21%	79%	55
GR	23%	13%	56%	8%	86%	11%	3%	0%	100%	40
HU	58%	0%	0%	43%	100%	0%	0%	63%	37%	79
IE	23%	13%	56%	8%	86%	11%	3%	28%	72%	42
IT	58%	0%	0%	43%	100%	0%	0%	26%	74%	56
LV	23%	13%	56%	8%	100%	0%	0%	0%	100%	43
LT	42%	32%	0%	27%	100%	0%	0%	22%	78%	56
NL	23%	13%	56%	8%	100%	0%	0%	15%	85%	51
PL	23%	13%	56%	8%	100%	0%	0%	24%	76%	57
PT	23%	13%	56%	8%	0%	0%	100%	6%	94%	40
RO	23%	13%	56%	8%	89%	11%	3%	-	-	-
SK	23%	13%	56%	8%	86%	11%	3%	38%	62%	64
SI	42%	32%	0%	27%	86%	11%	3%	10%	90%	40
ES	23%	13%	56%	8%	86%	11%	3%	13%	87%	48
SE	27%	0%	60%	12%	100%	0%	0%	41%	59%	69
GB	27%	0%	60%	12%	100%	0%	0%	57%	43%	80

The NREAPs [12] do not provide information concerning biofuel feedstock shares. For allocation of demanded biofuel to crop types we applied two steps. In a first step shares are set to the EU-level value [Table 2]. In a second step the projected production quantities based on the 1xNREAP scenario in 2010 for the listed crops [in absolute terms] are compared to FAOSTAT statistics [22]. In case the FAOSTAT production quantity is 0, the feedstock share is set to 0%. The leftover percentage is distributed in equal parts to the other crops. In case there are major inconsistencies between FAOSTAT and projected production quantities the feedstock shares are adjusted in order to minimize these inconsistencies.

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[1] Based on BioGrace [41]

[2] Domestic vales (corrected for imports and advanced biofuels); based on NREAPs [12]

[3] Weighted mean based on assumed feedstock productivity. Firstly the assumed feedstock productivity is weighted with assumed biofuel feedstock shares, secondly the resulting values for bioethanol and biodiesel are weighted with biofuel shares.

Member State level result table for scenario 1xNREAP with technological change

1xNREAP, Technological change, 2005-2020: Domestic 1st gen. biofuel production according to NREAP

		Energy demand			Biomass demand		Land-use change / GHG emissions					LCA of biofuel					
		2005	2020	2020	2005	2020	Food and Biofuel production			Food	Biofuel	GHG emissions			Allocation		
Country	ISO	1st gen. biofuels (bioethanol / biodiesel)		transport sector share	feedstock for 1st gen. biofuel production (0)		total LUC area (1)	total GHG emissions(2)	GHG emissions (2)	baseline GHG emissions (2)	attributable GHG emissions (2)	e_l (2,3)	$e_{ec}+e_p$ $+e_{td}$ (4)	E_B (5)	of GHG emissions to biofuel	allocated E_B	GHG emission saving (6)
		PJ	PJ	%	Mt	Mt	10^6 ha	$MtCO_{2eq}\ a^{-1}$	$tCO_{2eq}\ ha^{-1}\ a^{-1}$	$tCO_{2eq}\ ha^{-1}\ a^{-1}$	$tCO_{2eq}\ ha^{-1}\ a^{-1}$	$gCO_{2eq}\ MJ^{-1}$	$gCO_{2eq}\ MJ^{-1}$	$gCO_{2eq}\ MJ^{-1}$	%	$gCO_{2eq}\ MJ^{-1}$	%
AT	40	0	13	4%	0	3	0.27	1.8	6.7	-3.3	10.0	185	40	225	58%	131	-56%
BE	56	0	28	8%	0	5	0.48	2.5	5.1	-1.8	6.9	136	41	177	60%	105	-26%
BG	100	0	1	1%	0	0	0.42	-1.0	-2.4	-3.8	1.4	35	43	78	56%	44	48%
CZ	203	0	12	4%	0	2	0.33	1.0	3.1	-5.0	8.1	141	40	182	59%	106	-27%
DK	208	0	0	0%	0	0	0.18	-1.3	-7.1	-7.1	0.0						
EE	233	0	4	10%	0	1	0.22	2.0	8.9	1.6	7.3	175	46	220	59%	130	-55%
FI	246	0	16	9%	0	3	0.57	7.2	12.5	-1.2	13.7	235	41	276	60%	167	-99%
FR	250	16	128	7%	3	25	2.74	9.1	3.3	-1.7	5.1	97	41	138	58%	80	5%
DE	276	73	83	4%	12	15	1.89	-3.5	-1.8	-3.8	2.0	36	40	76	60%	46	45%
GR	300	0	8	3%	0	1	0.11	-0.2	-1.7	-1.4	-0.3	-7	41	34	56%	19	77%
HU	348	0	20	9%	0	5	0.45	1.4	3.2	-2.3	5.5	69	39	108	62%	67	20%
IE	372	0	6	2%	0	1	0.29	2.0	6.8	2.1	4.7	111	44	155	59%	91	-9%
IT	380	7	53	4%	1	11	1.30	1.1	0.9	-5.1	6.0	107	40	147	58%	86	-2%
LV	428	0	0	1%	0	0	0.10	0.0	0.3	0.1	0.2	4	41	46	59%	27	68%
LT	440	0	7	10%	0	1	0.52	2.0	3.7	-2.4	6.2	111	40	151	60%	91	-8%
NL	528	0	11	2%	0	2	0.49	3.8	7.8	2.1	5.7	111	41	151	60%	90	-8%
PL	616	2	72	9%	0	13	1.97	6.6	3.3	-2.2	5.6	98	40	138	60%	83	1%
PT	620	0	20	8%	0	3	0.43	1.9	4.4	-0.3	4.8	120	32	152	63%	96	-14%
RO	642	0	0	0%	0	0	1.05	-2.3	-2.2	-2.2	0.0						
SK	703	0	5	5%	0	1	0.28	0.8	2.8	-1.2	4.0	63	40	102	60%	61	27%
SI	705	0	8	10%	0	1	1.73	23.2	13.4	2.2	11.2	283	42	325	56%	182	-118%
ES	724	11	126	10%	2	23	1.73	4.8	2.7	-1.0	3.7	77	41	118	57%	68	19%
SE	752	2	18	5%	0	4	0.23	1.6	7.0	-4.9	12.0	172	40	212	62%	131	-57%
GB	826	0	22	1%	0	5	1.24	3.1	2.5	0.7	1.8	23	40	62	63%	39	53%
EU		111	660	5%	20	126	19	68	3.5	-2.0	5.5	103	41	144	59%	85	-2%

(0) Biofuel demand is allocated to feedstock according to feedstock shares listed above

(1) Conversions from non-cropland to cropland and vice versa

(2) Annualized (20 year basis)

(3) GHG emissions from carbon stock changes caused by land-use change due to biofuel production; obtained by the quotient of biofuel GHG emissions from land-use change and productivity of feedstock

(4) Biofuel GHG emissions from cultivation (e_{ec}), processing (e_p), transport and distribution (e_{td})

(5) Total GHG emissions from biofuel use

(6) Compared to fossil fuel GHG emissions: $E_F = 83.8\ gCO_{2eq}\ MJ^{-1}$; Saving = $(E_F-E_B)/E_F$: negative values indicate that the GHG performance of biofuel use is inferior to fossil fuel use; EU target: at least 35%

Member State level result table for scenario 1xNREAP without technological change

1xNREAP, No technological change, 2005-2020: Domestic 1st gen. biofuel production according to NREAP

		Energy demand			Biomass demand		Land-use change / GHG emissions					LCA of biofuel					
		2005	2020	2020	2005	2020	Food and Biofuel production			Food	Biofuel	GHG emissions			Allocation		
Country	ISO	1st gen. biofuels (bioethanol / biodiesel)		transport sector share	feedstock for 1st gen. biofuel production (0)		total LUC area (1)	total GHG emissions(2)	GHG emissions (2)	baseline GHG emissions (2)	attributable GHG emissions (2)	e_l (2,3)	e_{ec}+e_p +e_{td} (4)	E_B (5)	of GHG emissions to biofuel	allocated E_B	GHG emission saving (6)
		PJ	PJ	%	Mt	Mt	10^6 ha	$MtCO_{2eq}$ a^{-1}	tCO_{2eq} ha^{-1} a^{-1}	tCO_{2eq} ha^{-1} a^{-1}	tCO_{2eq} ha^{-1} a^{-1}	gCO_{2eq} MJ^{-1}	gCO_{2eq} MJ^{-1}	gCO_{2eq} MJ^{-1}	%	gCO_{2eq} MJ^{-1}	%
AT	40	0	13	4%	0	3	0.38	2.6	6.8	-1.4	8.2	152	45	196	58%	114	-36%
BE	56	0	28	8%	0	5	0.60	2.9	4.9	0.2	4.8	93	45	139	60%	82	2%
BG	100	0	1	1%	0	0	0.30	-0.2	-0.6	-2.6	2.0	52	47	99	56%	56	33%
CZ	203	0	12	4%	0	2	0.50	2.6	5.2	0.8	4.4	77	45	121	59%	71	15%
DK	208	0	0	0%	0	0	0.06	-0.1	-1.9	-1.9	0.0						
EE	233	0	4	10%	0	1	0.30	2.6	8.6	0.0	8.6	206	51	257	59%	152	-81%
FI	246	0	16	9%	0	3	0.72	9.0	12.5	2.0	10.6	182	45	227	60%	137	-64%
FR	250	16	128	7%	3	25	3.21	13.7	4.3	1.2	3.0	58	45	103	58%	60	29%
DE	276	73	83	4%	12	15	1.40	0.8	0.6	-1.7	2.2	41	44	85	60%	51	39%
GR	300	0	8	3%	0	1	0.08	-0.1	-1.2	-1.4	0.2	6	46	52	56%	29	65%
HU	348	0	20	9%	0	5	0.74	2.3	3.2	-2.0	5.1	65	43	108	62%	67	20%
IE	372	0	6	2%	0	1	0.36	2.6	7.3	3.7	3.6	84	49	133	59%	78	6%
IT	380	7	53	4%	1	11	2.41	-0.8	-0.3	0.0	-0.3	-5	45	39	58%	23	73%
LV	428	0	0	1%	0	0	0.08	0.2	2.8	1.5	1.3	30	46	76	59%	44	47%
LT	440	0	7	10%	0	1	0.65	3.3	5.1	-0.7	5.8	104	45	149	60%	89	-7%
NL	528	0	11	2%	0	2	0.49	4.2	8.5	5.6	2.9	57	45	103	60%	61	27%
PL	616	2	72	9%	0	13	2.92	10.8	3.7	-1.2	4.9	86	45	131	60%	79	6%
PT	620	0	20	8%	0	3	0.40	2.1	5.3	5.5	-0.2	-5	35	30	63%	19	77%
RO	642	0	0	0%	0	0	0.65	-0.6	-1.0	-1.0	0.0						
SK	703	0	5	5%	0	1	0.32	1.5	4.7	1.0	3.7	58	44	102	60%	61	28%
SI	705	0	8	10%	0	1	1.74	23.3	13.4	5.2	8.2	207	47	254	56%	142	-70%
ES	724	11	126	10%	2	23	2.66	7.4	2.8	0.2	2.6	53	45	99	57%	56	33%
SE	752	2	18	5%	0	4	0.38	2.6	6.9	-4.7	11.6	167	45	211	62%	131	-56%
GB	826	0	22	1%	0	5	1.10	5.0	4.6	2.3	2.3	29	44	73	63%	46	45%
EU		111	660	5%	20	126	22	98	4.4	0.2	4.1	77	45	122	59%	73	13%

(0) Biofuel demand is allocated to feedstock according to feedstock shares listed above

(1) Conversions from non-cropland to cropland and vice versa

(2) Annualized (20 year basis)

(3) GHG emissions from carbon stock changes caused by land-use change due to biofuel production; obtained by the quotient of biofuel GHG emissions from land-use change and productivity of feedstock

(4) Biofuel GHG emissions from cultivation (e_{ec}), processing (e_p), transport and distribution (e_{td})

(5) Total GHG emissions from biofuel use

(6) Compared to fossil fuel GHG emissions: E_F = 83.8 gCO_{2eq} MJ^{-1}; Saving = (E_F-E_B)/E_F; negative values indicate that the GHG performance of biofuel use is inferior to fossil fuel use; EU target: at least 35%

Member State level result table for scenario 2xNREAP with technological change

2xNREAP, Technological change, 2005-2020: Two times NREAP domestic 1st gen. biofuel production for 2020

		Energy demand			Biomass demand		Land-use change / GHG emissions					LCA of biofuel					
		2005	2020	2020	2005	2020	Food and Biofuel production			Food	Biofuel	GHG emissions			Allocation		
Country	ISO	1st gen. biofuels (bioethanol / biodiesel)		transport sector share	feedstock for 1st gen. biofuel production (0)		total LUC area (1)	total GHG emissions(2)	GHG emissions (2)	baseline GHG emissions (2)	attributable GHG emissions (2)	e_l (2,3)	$e_{ec}+e_p$ $+e_{td}$ (4)	E_B (5)	of GHG emissions to biofuel	allocated E_B	GHG emission saving (6)
		PJ	PJ	%	Mt	Mt	10^6 ha	$MtCO_{2eq}\,a^{-1}$	$tCO_{2eq}\,ha^{-1}\,a^{-1}$	$tCO_{2eq}\,ha^{-1}\,a^{-1}$	$tCO_{2eq}\,ha^{-1}\,a^{-1}$	$gCO_{2eq}\,MJ^{-1}$	$gCO_{2eq}\,MJ^{-1}$	$gCO_{2eq}\,MJ^{-1}$	%	$gCO_{2eq}\,MJ^{-1}$	%
AT	40	0	25	7%	0	5	0.62	4.3	6.9	-3.3	10.2	188	40	228	58%	133	-58%
BE	56	0	55	15%	0	9	0.98	5.5	5.6	-1.8	7.4	146	41	187	60%	111	-33%
BG	100	0	2	2%	0	0	0.31	0.2	0.7	-3.8	4.5	116	43	158	56%	89	-7%
CZ	203	0	23	8%	0	5	0.66	3.1	4.7	-5.0	9.7	170	40	210	59%	123	-47%
DK	208	0	0	0%	0	0	0.18	-1.3	-7.1	-7.1	0.0						
EE	233	0	7	19%	0	1	0.47	4.3	9.0	1.6	7.4	176	46	222	59%	131	-56%
FI	246	0	32	19%	0	6	1.09	14.2	13.0	-1.2	14.2	243	41	284	60%	172	-105%
FR	250	16	255	14%	3	50	4.61	21.5	4.7	-1.7	6.4	123	41	164	58%	95	-13%
DE	276	73	166	8%	12	30	1.52	5.1	3.4	-3.8	7.2	131	40	171	60%	103	-23%
GR	300	0	17	6%	0	3	0.11	-0.2	-1.7	-1.4	-0.3	-7	41	34	56%	19	77%
HU	348	0	41	18%	0	11	1.11	5.0	4.5	-2.3	6.8	86	39	125	62%	77	8%
IE	372	0	12	5%	0	2	0.53	3.7	7.1	2.1	5.0	118	44	162	59%	95	-14%
IT	380	7	106	7%	1	22	2.57	2.2	0.9	-5.1	6.0	107	40	147	58%	86	-2%
LV	428	0	1	1%	0	0	0.09	0.2	2.6	0.1	2.5	58	41	99	59%	58	31%
LT	440	0	14	19%	0	3	0.89	5.8	6.6	-2.4	9.0	161	40	202	60%	121	-45%
NL	528	0	21	5%	0	4	0.89	7.0	7.8	2.1	5.8	112	41	153	60%	91	-9%
PL	616	2	145	17%	0	27	4.93	19.3	3.9	-2.2	6.1	108	40	148	60%	89	-7%
PT	620	0	39	16%	0	6	0.45	1.8	4.0	-0.3	4.3	108	32	139	63%	88	-5%
RO	642	0	0	0%	0	0	1.05	-2.3	-2.2	-2.2	0.0						
SK	703	0	11	9%	0	2	0.45	2.1	4.6	-1.2	5.8	90	40	130	60%	78	8%
SI	705	0	16	20%	0	3	1.72	23.2	13.4	2.2	11.3	284	42	326	56%	183	-118%
ES	724	11	252	19%	2	47	3.05	8.3	2.7	-1.0	3.7	77	41	118	57%	68	19%
SE	752	2	36	10%	0	8	0.71	4.9	6.8	-4.9	11.8	170	40	210	62%	130	-55%
GB	826	0	43	2%	0	11	1.08	4.8	4.5	0.7	3.8	48	40	87	63%	55	34%
EU		111	1320	10%	20	252	30	143	4.7	-2.0	6.7	126	41	166	59%	99	-18%

(0) Biofuel demand is allocated to feedstock according to feedstock shares listed above

(1) Conversions from non-cropland to cropland and vice versa

(2) Annualized (20 year basis)

(3) GHG emissions from carbon stock changes caused by land-use change due to biofuel production; obtained by the quotient of biofuel GHG emissions from land-use change and productivity of feedstock

(4) Biofuel GHG emissions from cultivation (e_{ec}), processing (e_p), transport and distribution (e_{td})

(5) Total GHG emissions from biofuel use

(6) Compared to fossil fuel GHG emissions: E_F = 83.8 $gCO_{2eq}\,MJ^{-1}$; Saving = $(E_F-E_B)/E_F$; negative values indicate that the GHG performance of biofuel use is inferior to fossil fuel use; EU target: at least 35%

Member State level result table for scenario 2xNREAP without technological change

2xNREAP, No technological change, 2005-2020: Two times NREAP domestic 1st gen. biofuel production for 2020

		Energy demand			Biomass demand		Land-use change / GHG emissions					LCA of biofuel					
		2005	2020	2020	2005	2020	Food and Biofuel production			Food	Biofuel	GHG emissions			Allocation		
Country	ISO	1st gen. biofuels (bioethanol / biodiesel)		transport sector share	feedstock for 1st gen. biofuel production (0)		total LUC area (1)	total GHG emissions(2)	GHG emissions (2)	baseline GHG emissions (2)	attributable GHG emissions (2)	e_l (2,3)	$e_{ec}+e_p+e_{td}$ (4)	E_B (5)	of GHG emissions to biofuel	allocated E_B	GHG emission saving (6)
		PJ	PJ	%	Mt	Mt	10^6 ha	$MtCO_{2eq}\ a^{-1}$	$tCO_{2eq}\ ha^{-1}\ a^{-1}$	$tCO_{2eq}\ ha^{-1}\ a^{-1}$	$tCO_{2eq}\ ha^{-1}\ a^{-1}$	$gCO_{2eq}\ MJ^{-1}$	$gCO_{2eq}\ MJ^{-1}$	$gCO_{2eq}\ MJ^{-1}$	%	$gCO_{2eq}\ MJ^{-1}$	%
AT	40	0	25	7%	0	5	0.75	5.5	7.3	-1.4	8.7	160	45	205	58%	119	-42%
BE	56	0	55	15%	0	9	1.14	6.4	5.6	0.2	5.4	107	45	152	60%	91	-8%
BG	100	0	2	2%	0	0	0.52	0.9	1.7	-2.6	4.3	108	47	156	56%	88	-5%
CZ	203	0	23	8%	0	5	0.93	4.8	5.2	0.8	4.4	77	45	121	59%	71	15%
DK	208	0	0	0%	0	0	0.06	-0.1	-1.9	-1.9	0.0						
EE	233	0	7	19%	0	1	0.56	5.3	9.5	0.0	9.5	227	51	278	59%	164	-95%
FI	246	0	32	19%	0	6	1.23	16.2	13.2	2.0	11.2	192	45	237	60%	144	-71%
FR	250	16	255	14%	3	50	5.70	27.7	4.8	1.2	3.6	70	45	115	58%	66	21%
DE	276	73	166	8%	12	30	1.93	11.3	5.9	-1.7	7.6	138	44	182	60%	110	-31%
GR	300	0	17	6%	0	3	0.08	-0.1	-1.2	-1.4	0.2	6	46	52	56%	29	65%
HU	348	0	41	18%	0	11	1.52	5.8	3.8	-2.0	5.8	73	43	116	62%	72	14%
IE	372	0	12	5%	0	2	0.61	4.5	7.3	3.7	3.6	85	49	134	59%	79	6%
IT	380	7	106	7%	1	22	2.51	4.2	1.7	0.0	1.7	30	45	75	58%	44	48%
LV	428	0	1	1%	0	0	0.07	0.4	6.1	1.5	4.6	107	46	153	59%	90	-7%
LT	440	0	14	19%	0	3	1.04	7.4	7.1	-0.7	7.7	139	45	184	60%	111	-32%
NL	528	0	21	5%	0	4	0.89	7.7	8.7	5.6	3.1	60	45	105	60%	63	25%
PL	616	2	145	17%	0	27	6.25	27.0	4.3	-1.2	5.5	97	45	142	60%	85	-2%
PT	620	0	39	16%	0	6	0.47	2.2	4.6	5.5	-0.9	-23	35	13	63%	8	90%
RO	642	0	0	0%	0	0	0.66	-0.6	-1.0	-1.0	0.1						
SK	703	0	11	9%	0	2	0.53	2.7	5.1	1.0	4.2	65	44	109	60%	65	22%
SI	705	0	16	20%	0	3	1.75	23.3	13.3	5.2	8.1	205	47	251	56%	141	-68%
ES	724	11	252	19%	2	47	3.80	10.4	2.7	0.2	2.5	53	45	98	57%	56	33%
SE	752	2	36	10%	0	8	0.85	5.8	6.9	-4.7	11.6	166	45	211	62%	130	-56%
GB	826	0	43	2%	0	11	1.13	7.0	6.2	2.3	3.9	49	44	93	63%	59	30%
EU		111	1320	10%	20	252	35	186	5.3	0.2	5.1	95	45	140	59%	83	1%

(0) Biofuel demand is allocated to feedstock according to feedstock shares listed above

(1) Conversions from non-cropland to cropland and vice versa

(2) Annualized (20 year basis)

(3) GHG emissions from carbon stock changes caused by land-use change due to biofuel production; obtained by the quotient of biofuel GHG emissions from land-use change and productivity of feedstock

(4) Biofuel GHG emissions from cultivation (e_{ec}), processing (e_p), transport and distribution (e_{td})

(5) Total GHG emissions from biofuel use

(6) Compared to fossil fuel GHG emissions: $E_F = 83.8\ gCO_{2eq}\ MJ^{-1}$; Saving = $(E_F-E_B)/E_F$; negative values indicate that the GHG performance of biofuel use is inferior to fossil fuel use; EU target: at least 35%