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# Quantifying the climate impacts of albedo changes due to biofuel production: a comparison with biogeochemical effects

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## Abstract

Lifecycle analysis is a tool widely used to evaluate the climate impact of greenhouse gas emissions attributable to the production and use of biofuels. In this paper we employ an augmented lifecycle framework that includes climate impacts from changes in surface albedo due to land use change. We consider eleven land-use change scenarios for the cultivation of biomass for middle distillate fuel production, and compare our results to previous estimates of lifecycle greenhouse gas emissions for the same set of land-use change scenarios in terms of CO<sub>2</sub>e per unit of fuel energy. We find that two of the land-use change scenarios considered demonstrate a warming effect due to changes in surface albedo, compared to conventional fuel, the largest of which is for replacement of desert land with salicornia cultivation. This corresponds to 222 gCO<sub>2</sub>e/MJ, equivalent to 3890% and 247% of the lifecycle GHG emissions of fuels derived from salicornia and crude oil, respectively. Nine of the land-use change scenarios considered demonstrate a cooling effect, the largest of which is for the replacement of tropical rainforests with soybean cultivation. This corresponds to -161 gCO<sub>2</sub>e/MJ, or -28% and -178% of the lifecycle greenhouse gas emissions of fuels derived from soybean and crude oil, respectively. These results indicate that changes in surface albedo have the potential to dominate the climate impact of biofuels, and we conclude that accounting for changes in surface albedo is necessary for a complete assessment of the aggregate climate impacts of biofuel production and use.

Keywords: albedo, biofuels, climate, lifecycle


 Online supplementary data available from [stacks.iop.org/ERL/9/024015/mmedia](http://stacks.iop.org/ERL/9/024015/mmedia)

## 1. Introduction

Biofuels may hold promise to promote energy security, reduce the environmental impact of transportation and foster economic development. For these reasons, many countries have enacted policies to encourage their production (EU 2009,

US EPA 2013). In the US, biofuel production for transportation aims to replace 30% of petroleum consumption by 2030 (Perlack *et al* 2005, US Department of Energy 2011). Targets are also set for the EU (10% replacement of diesel and gasoline by 2020; EU 2009) and other countries such as China (2 million tons of biodiesel by 2020; Koizumi 2011) and Indonesia (20% replacement of diesel and gasoline by 2025; Zhou and Thomson 2009).

Historically, environmental assessments of biofuels have focused on biogeochemical effects (i.e. greenhouse gas (GHG)

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emissions) directly or indirectly attributable to the lifecycle of the fuel. Emissions are considered for all relevant lifecycle steps, including feedstock cultivation, extraction, and transportation as well as fuel production, distribution, and combustion (Kim and Dale 2005, Larson 2006, Lardon *et al* 2009, Yee *et al* 2009, Stratton *et al* 2010, Van der Voet *et al* 2010, Guinée *et al* 2011). Land-use change (LUC) to cultivate biomass feedstock for biofuel production may lead to GHG emissions if it changes the amount of carbon stored in vegetation and soil (Stratton *et al* 2010).

Distinct from assessing the biogeochemical effects, there is limited research focused on the biogeophysical effects of LUC for biomass feedstock cultivation. Biogeophysical effects include changes in surface albedo (Betts 2000, Lee *et al* 2011), evapotranspiration (Pitman *et al* 2009, Georgescu *et al* 2011), surface roughness/canopy resistance (Lean and Rowntree 1993, Betts 2007, Georgescu *et al* 2009), leaf area index and rooting depth of the vegetation (Georgescu *et al* 2009). Of these, the LUC-induced change in surface albedo is considered the dominant biogeophysical effect at the global scale (Betts 2000, 2001, Claussen *et al* 2001, Bala *et al* 2007). A change in albedo alters the surface reflectivity of sunlight (the incoming shortwave radiation), thus changing the Earth's radiative balance. Albedo changes can be quantified in terms of global radiative forcing (RF) (Betts 2000, Georgescu *et al* 2011, Bright *et al* 2012, Cherubini *et al* 2012), which can be expressed in terms of GHG equivalent emissions (Betts 2001, Bird *et al* 2008). This allows for a direct comparison against the biogeochemical effects calculated by traditional LCA.

In contrast, additional biogeophysical effects such as evapotranspiration and surface roughness cannot be adequately expressed in terms of global RF (Davin *et al* 2007, Betts 2011, Cherubini *et al* 2012), although they may be relevant at a local scale (Bounoua *et al* 2002, Georgescu *et al* 2011). In previous work, the climate impact of albedo changes has been assessed to describe the effect of forestation policies (Rautiainen *et al* 2009, Lohila *et al* 2010, Rautiainen *et al* 2011). Recent studies have also attempted to evaluate the albedo effect of biomass feedstock cultivation, using either numerical models (Georgescu *et al* 2011, Anderson-Teixeira *et al* 2012, Hallgren *et al* 2013, Anderson *et al* 2013) or satellite measurements (Bright *et al* 2011, Loarie *et al* 2011, Cherubini *et al* 2012). The results of those analyses suggest that albedo effects are potentially as important as the biogeochemical effects assessed by traditional LCA (Georgescu *et al* 2011, Anderson-Teixeira *et al* 2012). The assessments that are available in the literature often focus only on a single feedstock (Georgescu *et al* 2011, Bright *et al* 2011, Loarie *et al* 2011) and are based on different methodologies, making cross-study comparison difficult.

In this study we perform an assessment of the LUC-induced albedo effects of a range of LUC scenarios by considering the cultivation of five different biomass feedstocks (switchgrass, soybean, palm, rapeseed and salicornia) and compare these effects to the biogeochemical effects quantified by traditional LCA. To the best of our knowledge, this is the first study to consider the albedo effects from a broad range of feedstocks using direct satellite measurements, and the first to

quantify and compare the albedo effect of replacing an original land use with the cultivation of palm, rapeseed or salicornia, in particular. The LUC scenarios considered are derived from Stratton *et al* (2010, 2011a) and the albedo effects are presented in terms of gCO<sub>2</sub>e/MJ of renewable middle distillate (MD) fuel, which is the fuel considered in the Stratton *et al* (2011a) lifecycle analysis. This enables a consistent comparison of the LUC-induced albedo effect, the biogeochemical effects from LUC, and the GHG emissions from the production of renewable MD fuels.

## 2. Methodology

In this study, we evaluate the induced albedo effect of a number of discrete LUC scenarios. Each of these scenarios is evaluated at multiple geographic locations in order to account for variability in surface and meteorological conditions within the same land types involved in the LUC. Satellite measurements of albedo and transmittance parameters are retrieved for each geographic location of interest, and an analytical radiative balance model is used to convert the albedo changes into a RF, then into equivalent GHG emissions.

### 2.1. LUC scenarios

We consider eleven LUC scenarios, comprised of five different biomass feedstocks for up to three original land uses each, as shown in table 1. Each scenario is restricted to one geographic region. The scenarios are consistent between this study and the traditional LCA study that we use as a reference (Stratton *et al* 2010; LUC combinations S1, S2, P1, P2, P3, H1), wherever possible. The switchgrass and rapeseed scenarios are redefined due to ambiguities in the reference LCA study. In Stratton *et al* (2010), switchgrass cultivation is assumed to take place on generic carbon-depleted soils. In this study we consider three possible LUC scenarios associated with carbon-depleted soils (McLaughlin *et al* 2002, Adler *et al* 2007): corn cultivation (LUC B1), soybean cultivation (LUC B2), and barren land (LUC B3) replaced by switchgrass cultivation. Furthermore, in the reference LCA rapeseed cultivation in Europe is assumed to take place on set-aside land, i.e. land areas temporarily removed from agricultural production (Stratton *et al* 2010). In this case we consider two LUC scenarios: corn cultivation (LUC R1) and uncultivated land (LUC R2) replaced by rapeseed cultivation. Table 1 also indicates the geographic region in which each LUC scenario is assumed to take place in the reference LCA (Stratton *et al* 2011a).

A minimum of four geographic locations are selected to describe each original land use type, and a minimum of eight combinations of biomass feedstock and original land use locations are used to define each of the 11 LUC scenarios shown in table 1. This multi-location approach allows for a more complete picture of the potential land conversions and the associated natural variability. The latitude and longitude of these locations are retrieved using current literature (e.g., Mosali *et al* 2013), satellite observations (e.g., Rhines 2008) and farming databases (e.g., FIC 2013), and are confirmed using the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type database (MCD12Q1) (NASA MODIS 2013a).

**Table 1.** Biomass feedstock types (first column) and original land uses from this study (second column), compared to the reference LCA from Stratton *et al* (2010) (fourth column). Each LUC scenario for which the albedo effect is calculated is associated to a LUC code (third column). Geographic regions (fifth column) are consistent with the reference LCA (Stratton *et al* 2010) for each LUC scenario, in order to enable comparison between albedo and biogeochemical effects.

Biomass feedstock type	Original land use (this study)	LUC code	Original land use (reference LCA) <sup>a</sup>	Region
Switchgrass	Corn cultivation	B1		Central US (Midwest-Northeast states)
	Soybean cultivation	B2	Carbon-depleted soil	
	Barren land	B3		
Soy	Cerrado grassland	S1	Cerrado grassland	Brazil (Central and Southern regions)
	Tropical rainforest	S2	Tropical rainforest	
Palm	Previously logged-over forest	P1	Previously logged-over forest	Southeast Asia (Malaysia and Indonesia)
	Tropical rainforest	P2	Tropical rainforest	
	Peat land rainforest	P3	Peat land rainforest	
Rapeseed	Corn cultivation	R1	Set-aside land	Europe (United Kingdom, France and Denmark)
	Uncultivated land	R2		
Salicornia	Desert	H1	Desert	Mexico (Sonora desert) and US (Southern states)

<sup>a</sup> Stratton *et al* (2010).

## 2.2. Albedo and transmittance data retrieval and calculation

Black-sky shortwave (BSW) broadband albedo coefficients (encompassing both the near infrared and visible spectra) are retrieved for each biomass feedstock and original land use pairing,  $i$ , that represents a specific LUC scenario. BSW albedo coefficients are obtained from the MODIS satellite database MCD43A3 (NASA MODIS 2013b) and vetted using a separate MODIS database (MCD43A2; NASA MODIS 2013c). Albedo data from the MODIS database are produced every 8 days and are linearly interpolated to obtain daily albedo evaluations for a full year. In case of missing or low quality data, the time interpolation is performed between the two closest acceptable observations. The average daily BSW albedo for each  $i$  is obtained for a full year by averaging the daily values retrieved for three reference years (2009, 2010 and 2011), in order to account for annual variability in local conditions. Biases in each individual albedo observation are reduced by taking the space average across the 500 m × 500 m cell where the location under investigation is found and the eight cells surrounding it. Consistency between the land-use type of these cells is verified using the MODIS Land Cover Type database (NASA MODIS 2013a). Table 2 shows the yearly-averaged BSW albedo, retrieved and processed as described, for each land use type considered in the LUC scenarios from table 1. The BSW albedos in table 2 are given as mean, minimum and maximum values among the yearly-averaged albedos retrieved for all the sample locations representing each specific land use type.

For each biomass feedstock type and original land use pairing  $i$ , representing a LUC scenario from table 1 we evaluate the albedo effect as the difference in RF induced by the conversion of the original land use to biomass feedstock cultivation. The geographical location and conditions of radiative transmittance are kept the same as that of the original land use; i.e. feedbacks between albedo changes and local weather/cloudiness conditions are not accounted for. For each

$i$ , the planetary albedo change is computed as a function of the day of the year  $d$ :

$$\Delta\alpha_i(d) = K_{T \text{ orig},i}(d)T_a[\alpha_{\text{bio},i}(d) - \alpha_{\text{orig},i}(d)] \quad (1)$$

where  $\alpha_{\text{bio},i}$  and  $\alpha_{\text{orig},i}$  are the daily cloud-free shortwave albedo coefficients for biomass feedstock cultivation and the original land use, respectively, obtained from the MODIS database (NASA MODIS 2013b) and averaged in time and space as previously described.  $K_{T \text{ orig},i}$  is the mean daily all-sky clearness index for the original land use point, and  $T_a$  is the transmittance factor, as in Bright *et al* (2012). The calculation of planetary albedo differences from clear-sky surface albedo values in equation (1) follows a procedure widely reported in the literature (Lenton and Vaughan 2009, Muñoz *et al* 2010, Bright *et al* 2012, Cherubini *et al* 2012). Local mean daily values of  $K_{T \text{ orig},i}$  are constant for each month and are retrieved from the NASA Atmospheric Science and Data Center (ASDC) database, which provides monthly 22-year averages of the all-sky clearness index (including maximum and minimum bounds) (NASA ASDC 2013). The transmittance factor  $T_a$  is chosen as a global annual average of 0.854, consistent with previous findings and modeling comparisons (Lenton and Vaughan 2009, Muñoz *et al* 2010, Cherubini *et al* 2012, Bright and Kvalevåg 2013).

## 2.3. Radiative forcing (RF) model

The planetary albedo change due to biomass feedstock cultivation on land originally used for some other purpose, found in (1), alters the radiative balance of the Earth which can be quantified as a radiative forcing. This is equal to the time integral of the product of daily albedo variation (1) and daily radiative flux at the top of the atmosphere  $R_{\text{TOA},i}(d)$ , calculated at the original land use location (Bright *et al* 2012, Cherubini *et al* 2012). For each biomass feedstock and original land use pairing,  $i$ , the yearly global RF (measured in  $\text{W m}^{-2}$ )

is therefore:

$$\Delta RF_{\text{global},i} = \left\{ -\frac{1}{365} \sum_{d=1}^{365} [R_{\text{TOA},i}(d) \cdot \Delta\alpha_i(d)] \right\} \cdot \frac{A_a}{A_{\text{earth}}} \quad (2)$$

where  $A_a$  is the reference area subject to the albedo change, and  $A_{\text{earth}}$  is the total area of the earth. The RF associated with each of the LUC scenarios in table 1,  $\Delta RF_{\text{LUC}}$ , is calculated as the average of all the global yearly radiative forcings  $\Delta RF_{\text{global},i}$  found for all of the pairings,  $i$  representing the same LUC case.

#### 2.4. CO<sub>2</sub>-equivalent emission conversion

CO<sub>2</sub>e emissions per unit energy of biofuel produced (gCO<sub>2</sub>e/MJ) is a common metric adopted in LCA studies (Larson 2006, Adler *et al* 2007, Stratton *et al* 2010, 2011a). To establish direct comparison between albedo change effects and biogeophysical effects for the same LUC scenario, the global RF associated with each one of the LUC scenarios in table 1 is converted into CO<sub>2</sub>e. The correspondence between the RF induced by albedo changes and CO<sub>2</sub>e emissions is well established in the literature (Betts 2000, Bird *et al* 2008, Muñoz *et al* 2010, Joos *et al* 2013). First, RF is converted into a change in atmospheric carbon concentration  $\Delta C$  by using a logarithmic relation with the background carbon concentration (Betts 2000) (linearized for small perturbations). Positive RF (induced by a decrease in the land albedo) corresponds to carbon emissions, while negative RF corresponds to carbon sequestrations. The concentration  $\Delta C$  (in parts per million, ppm) is then converted into an equivalent carbon emission  $\Delta C_T$  per unit area subject to albedo change:

$$\Delta C_T = \left( \frac{1}{AF_{\text{TH}=100}} \right) \Delta C m_{\text{atm}} \left( \frac{M_C}{M_{\text{air}}} \right) \times \left( \frac{1}{A_a} \right) \frac{1}{10^6} \text{ (tC ha}^{-1}\text{)} \quad (3)$$

where  $m_{\text{atm}}$  is the total mass of the atmosphere (in tons),  $M_C$  and  $M_{\text{air}}$  are the molecular weights of carbon and air respectively (in g mol<sup>-1</sup>),  $A_a$  is expressed in hectares and  $AF_{\text{TH}=100}$  is the airborne emission fraction of CO<sub>2</sub> for a time horizon (TH) of 100 years, consistent with the reference biogeochemical impacts assessment by Stratton *et al* (2010). Finally, using data about the biomass yield, mass conversion factor, and specific energy conversion efficiencies, the carbon emission per unit area in (3) is converted into a CO<sub>2</sub>e emission per unit energy of the fuel produced. In order to evaluate the albedo effects under the same assumptions as the biogeochemical impacts, the resulting emissions are distributed over 30 years, as in the reference LCA (Stratton *et al* 2010).

In order to represent the magnitude of natural variability, we examine low, baseline, and high cases for each LUC scenario in table 1. The baseline cases utilize the mean of the RFs calculated for all the biomass feedstock and original land use pairings representing the same LUC scenario. Low and high cases utilize the maximum and minimum RFs calculated among the pairings used to simulate the same LUC scenario, and the upper and lower estimates of the relevant all-sky

clearness index from the ASDC database (NASA ASDC 2013). Variability in meteorological conditions is therefore accounted for.

The geographic locations and relevant physical parameters for all sample locations are given in the Supporting Information (SI available at [stacks.iop.org/ERL/9/024015/mmedia](http://stacks.iop.org/ERL/9/024015/mmedia)). A more detailed derivation of the albedo-emission conversion model and the yields and energy efficiencies of each biomass feedstock type are also discussed in the SI (available at [stacks.iop.org/ERL/9/024015/mmedia](http://stacks.iop.org/ERL/9/024015/mmedia)).

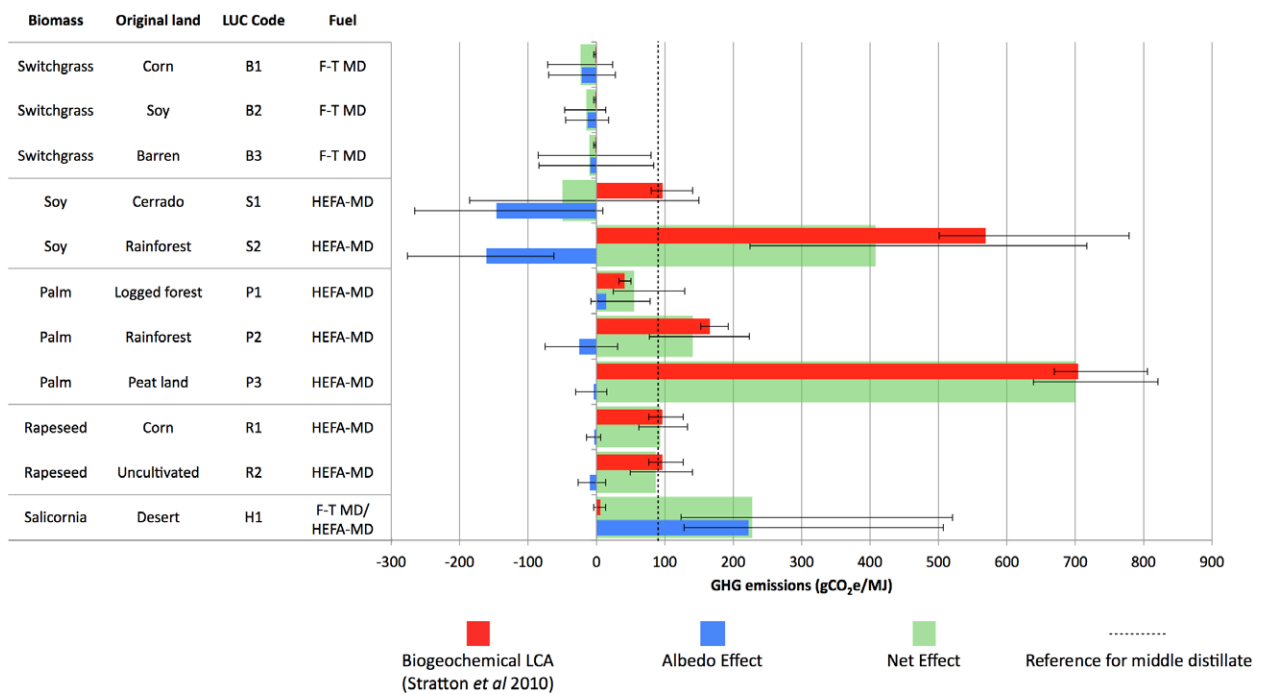
### 3. Results and discussion

The albedo effect for the eleven LUC scenarios is shown in figure 1 (blue bars) in terms of emissions or sequestrations of CO<sub>2</sub>e per unit energy of biofuel produced (gCO<sub>2</sub>e/MJ). The whisker bars represent low and high cases, corresponding to the minimum and maximum RF from the albedo changes induced by each LUC scenario, taking into account the variability of the albedo and meteorological conditions among the locations representative of the same LUC scenario.

The red bars in figure 1 show the biogeochemical impacts calculated in the reference LCA by Stratton *et al* (2010) for the same biomass feedstock cultivation and original land use pairings. The biogeochemical effects calculated in the reference study include GHG emissions from cultivation, harvesting, extraction and transportation of the biomass; processing of biomass into MD fuels; and transportation, distribution, and combustion of the finished fuel product. Non-CO<sub>2</sub> GHGs and emissions species from direct fuel combustion are not considered in the reference LCA. In the case of aviation, these effects can result in a doubling of CO<sub>2</sub>e direct fuel combustion emissions for a 100 year time horizon (Stratton *et al* 2011b). Only GHG emissions associated with direct LUC are considered in the reference LCA (Stratton *et al* 2010). Emissions from indirect LUC, which occurs if direct LUC disrupts the equilibrium between supply and demand for the displaced crop, and for downstream products relying on this crop (Plevin *et al* 2010), are not taken into account. The low and high ranges for the red bars in figure 1 reflect the variability of parameters used for LCA, such as process efficiency and biomass feedstock yield (Stratton *et al* 2010). The green bars in figure 1 represent the sum of albedo and biogeochemical effects. This net effect can be compared to the reference lifecycle emissions for conventional MD (90 gCO<sub>2</sub>e/MJ, dashed black line in figure 1), assumed to be equal to the results for conventional diesel from Stratton *et al* (2011a). We do not consider albedo effects attributable to conventional middle distillate fuels, since in this case land use change per unit energy of finished fuel is estimated to be two to three orders of magnitude lower than for biomass-based fuels (Yeh *et al* 2010).

#### 3.1. Switchgrass

The albedo change due to replacement of corn cultivation, soy cultivation and barren land with switchgrass (scenarios B1–B3) leads to a negative RF in the baseline results, the equivalent of a sequestration of CO<sub>2</sub>e. The effect is stronger when switchgrass replaces corn (LUC B1, −22 gCO<sub>2</sub>e/MJ) or soy (LUC B2, −13 gCO<sub>2</sub>e/MJ) than it is for



**Figure 1.** Climate impacts of biofuel production and use for different LUC scenarios. Each row of the table on the left contains a biomass feedstock type and original land use pairing, corresponding to a particular MD fuel, indicated in the last column. In the histogram, the blue bars indicate the impact of the albedo variations due to each LUC, in terms of CO<sub>2</sub>e per unit energy of fuel produced. The high and low cases include variability in the geographical locations and local meteorological conditions (as described in section 2.4). The red bars show the biogeochemical effects (i.e., the direct GHG emissions) as calculated in the reference LCA (Stratton *et al* 2010). The related whisker bars account for the variability of process efficiency and biomass feedstock yield (Stratton *et al* 2010). The green bars in the background show the net impact of considering albedo and biogeochemical effects in the baseline, low and high emission scenarios. Both albedo and biogeochemical effects are distributed over a time span of 30 years, consistent with Stratton *et al* (2010). The dashed black line indicates the results for conventional MD fuel from the reference LCA (Stratton *et al* 2010).

barren land (LUC B3, -9 gCO<sub>2</sub>e/MJ). A negative RF (or equivalently a cooling effect) for the conversion of land to switchgrass cultivation has also been computed by Georgescu *et al* (2011) (-0.0053 W m<sup>-2</sup>) and Anderson-Teixeira *et al* (2012) (-50 Mg CO<sub>2</sub>e ha<sup>-1</sup> 50 yr<sup>-1</sup>) however the disparate methodologies, metrics and LUC assumptions used in those studies do not allow a quantitative comparison with this work. The biogeochemical lifecycle impacts of renewable MD fuel production and use from switchgrass replacing carbon-depleted soils are estimated by Stratton *et al* (2010) to be nearly carbon neutral (-1.6 gCO<sub>2</sub>e/MJ). In absolute terms, the albedo impact of switchgrass cultivation for MD production is therefore 1380%, 813% and 563% greater than the biogeochemical lifecycle effects of corn, soybean, and barren land conversion, respectively. The net sum of albedo and biogeochemical effects is -23 gCO<sub>2</sub>e/MJ, -15gCO<sub>2</sub>e/MJ and -11 gCO<sub>2</sub>e/MJ for corn replacement (LUC B1), soy replacement (LUC B2) and barren land replacement (LUC B3), respectively. It should be noted that the high emission cases (high whisker bar limits) demonstrate that a net positive RF is also possible for these three LUC scenarios.

### 3.2. Soy

In figure 1, LUC S1 and S2 show that the albedo effect of replacing Brazilian Cerrado and tropical rainforest with

soybean cultivation results, in both cases, in a negative RF, equivalent to a cooling effect (-146 and -161 gCO<sub>2</sub>e/MJ, respectively). Soybean cultivation in Brazil generally exhibits a higher reflectivity (average albedo of 0.175, see table 2) than the savannah land of the Brazilian Cerrado (average albedo of 0.133) or than the dense dark tropical rainforest in the Amazon region (average albedo of 0.120). An albedo-induced CO<sub>2</sub>e reduction due to the establishment of soy cultivation in Brazil has also been found by Anderson-Teixeira *et al* (2012) (-70 MgCO<sub>2</sub>e ha<sup>-1</sup> 50 yr<sup>-1</sup>). The green bar in figure 1 for LUC S1 shows that, considering both the effects of albedo change and of biogeochemical effects in the baseline, low and high emission scenarios, the aggregate climate impact of the conversion of cerrado grassland to soybean cultivation is equivalent to a sequestration of 50 gCO<sub>2</sub>e/MJ. By adding the albedo effect to the biogeochemical results from the reference LCA, renewable MD from soybean cultivated on land that was previously Cerrado grassland exhibits a decrease in climate impact of 156% with respect to conventional MD (from 90 to -50 gCO<sub>2</sub>e/MJ). This reverts the results of the reference LCA which suggests that soybean derived MD has greater climate impact, in terms of lifecycle GHG emissions, than conventional MD (97 gCO<sub>2</sub>e/MJ versus 90 gCO<sub>2</sub>e/MJ) (Stratton *et al* 2010). In the case of tropical rainforest replacement with soybean cultivation (LUC S2), inclusion of the albedo effects does not revert the findings of

**Table 2.** Black-sky shortwave albedo for each land use type considered in this study. Albedo values are given as mean, minimum and maximum values among yearly-averaged BSW albedo coefficients retrieved for the sample locations representing a specific land use type. The number of sample locations for each land use type is indicated in the Table. Yearly-averaged BSW albedos at each location are obtained from the MODIS satellite database MCD43A3 (NASA MODIS 2013b), and treated as described in section 2.2.

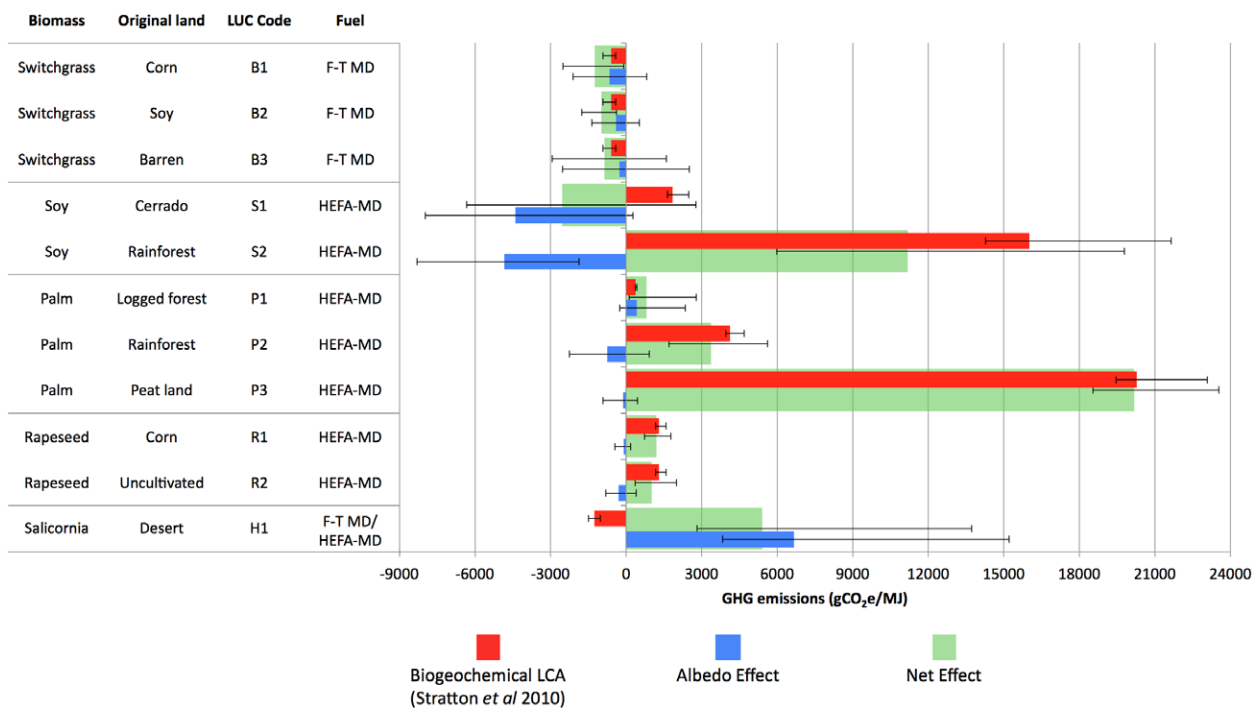
Land type	Number of samples	BSW albedo		
		Mean	Min	Max
Switchgrass field (US)	4	0.177	0.156	0.191
Soybean cultivation (Brazil)	6	0.175	0.139	0.204
Palm plantation (SE Asia)	14	0.088	0.045	0.134
Rapeseed field (Europe)	11	0.162	0.147	0.179
Salicornia cultivation (Mexico)	5	0.149	0.140	0.156
Corn field (US)	5	0.165	0.151	0.178
Soybean cultivation (US)	8	0.163	0.148	0.200
Barren land (US)	4	0.175	0.135	0.222
Cerrado grassland (Brazil)	4	0.133	0.122	0.148
Tropical rainforest (Brazil)	4	0.120	0.111	0.128
Previously logged-over forest (SE Asia)	9	0.125	0.093	0.138
Tropical rainforest (SE Asia)	4	0.066	0.033	0.103
Peat land rainforest (SE Asia)	4	0.091	0.046	0.129
Corn field (Europe)	11	0.156	0.145	0.174
Uncultivated land (Europe)	8	0.151	0.132	0.184
Desert land (South US/Mexico)	10	0.326	0.251	0.535

the reference LCA: the direct GHG emission calculated by the reference LCA (569 gCO<sub>2</sub>e/MJ) (Stratton *et al* 2010) is 453% larger than the impact attributable to the increase in albedo (−161 gCO<sub>2</sub>e/MJ).

### 3.3. Palm

Due to their leaf characteristics and plantation density, palms are characterized by the lowest average shortwave albedo (0.088, see table 2) among the biomass feedstock types considered in this study. Furthermore, palm is not harvested, meaning that the low albedo coefficient is nearly constant throughout the year. This accounts for the smaller cooling effect shown in figure 1 for the case of tropical rainforest replaced by palm plantations (LUC P2, −25 gCO<sub>2</sub>e/MJ) compared to the cooling effect occurring for soybean cultivation replacement

of tropical rainforest (LUC S2, −161 gCO<sub>2</sub>e/MJ). The low albedo of palm also accounts for the positive RF induced by conversion of previously logged-over forest (LUC P1), equivalent to a GHG emission of 14 gCO<sub>2</sub>e/MJ. Palm replacement of peat land rainforest (LUC P3) yields a relatively small sequestration of −4 gCO<sub>2</sub>e/MJ. For the aggregate climate impact of LUC P1, indicated by the green bar in figure 1, the baseline case of 55 gCO<sub>2</sub>/MJ remains below the conventional jet fuel baseline even if the albedo effect is included. If the albedo effect is included, the high emission case (high whisker bar limit, 129 gCO<sub>2</sub>e/MJ) is 43% larger than conventional MD, whereas the high emission case for the biogeochemical effects does not exceed the conventional MD reference. For LUC P2, while the baseline warming effect remains higher than that of conventional MD even if the albedo effect is included, the aggregate climate impact in the low emission



**Figure 2.** Climate impacts of direct LUC for different LUC scenarios. Each row of the table on the left contains a biomass feedstock type and original land use pairing, corresponding to a particular MD fuel, indicated in the last column. In the histogram, the blue bars indicate the instantaneous effect of changes in albedo due to LUC, in terms of CO<sub>2</sub> equivalent emissions per unit energy of fuel. The high and low cases include variability in the geographical locations and local meteorological conditions (as described in section 2.4). The red bars show the biogeochemical effects (i.e., LUC-induced GHG emissions) related exclusively to LUC, as calculated by Stratton *et al* (2010). The related whisker bars account for the variability in biomass feedstock yield (Stratton *et al* 2010). The green bars in the background show the aggregate climate impact of LUC considering albedo and biogeochemical effects in the baseline, low and high emission scenarios.

case (77 gCO<sub>2</sub>e/MJ) is below that of conventional MD, which was not the case in the reference LCA. For LUC P3, the biogeochemical effects from the reference LCA are so large (705 gCO<sub>2</sub>e/MJ) (Stratton *et al* 2010), that the inclusion of albedo effects does not change the total climate impact significantly.

### 3.4. Rapeseed

LUC R1 and R2 show the albedo effect of replacing corn or uncultivated land with rapeseed cultivation in Europe. In both cases a small cooling effect is found, -3gCO<sub>2</sub>e/MJ for LUC R1 and -10 gCO<sub>2</sub>e/MJ for LUC R2. According to the reference LCA, the biogeochemical effects of renewable MD fuel from rapeseed cultivated on previously set-aside land, yields a biogeochemical effect of 96 gCO<sub>2</sub>e/MJ (Stratton *et al* 2010). The contribution of the albedo effect is negligible for this set of LUC scenarios.

### 3.5. Salicornia

LUC H1 considers salicornia cultivation on land that was previously desert. The albedo of the desert (average of 0.326 from table 2) is much larger than the albedo of the salicornia cultivations (average of 0.149), since deserts are composed of smooth, clear sand, and are highly reflective of incoming solar radiation (Pielke and Avissar 1990). The large desert albedo accounts for the relatively large positive RF induced

by LUC H1, equivalent to 222 gCO<sub>2</sub>e/MJ. In comparison, the direct GHG emissions computed by the reference LCA are only 6 gCO<sub>2</sub>e/MJ (Stratton *et al* 2010). This result shows that production and use of renewable MD using salicornia grown on desert lands can have a larger warming effect than producing and using conventional MD.

Figure 2 shows a comparison between albedo effects and GHG emissions from LUC, excluding all the other stages accounted for in the reference LCA (Stratton *et al* 2010) (i.e. biomass cultivation and transport; feedstock to fuel conversion; and biofuel transport and combustion). This comparison is instructive since it shows the relative magnitude of the biogeochemical and biogeophysical effects that exclusively stem from (direct) alterations in land use. Both effects are evaluated as instantaneous CO<sub>2</sub>e emissions, not distributed across the reference 30-years time span as in figure 1 (see equation S19 in the SI available at [stacks.iop.org/ERL/9/024015/mmedia](http://stacks.iop.org/ERL/9/024015/mmedia)) but only across the first year of land use change. This is because the albedo effect is obtained using albedo differences and transmittance parameters averaged over a full year of variation, and carbon sequestration due to LUC is evaluated after a full year of vegetation replacement (Stratton *et al* 2010). Therefore, the results for albedo effects (blue bars) are directly proportional to the ones shown in figure 1. Results for LUC emissions (red bars) are instead proportionally smaller than the ones reported in figure 1, since they exclude steady-state transport, production and combustion emissions. The results



indicate that albedo effects are on the same order of magnitude as the traditional direct biogeochemical LUC emissions for most of the LUC scenarios considered.

#### 4. Conclusions

This study shows that changes to surface albedo due to biomass cultivation can have a significant impact on the aggregate climate impact of biofuels. The albedo effects of LUC related to biomass feedstock cultivation for biofuel production, shown in figure 1, are on the same order of magnitude as the biogeochemical effects calculated by traditional LCA for the same LUC scenarios. The largest effects are calculated for LUC scenarios S1 and H1. Renewable MD production from soybean cultivated on land that was previously cerrado grassland (LUC S1) is found to yield a net cooling effect, equivalent to  $-50 \text{ gCO}_2\text{e/MJ}$ . This makes renewable MD derived from soy oil a potentially viable alternative to conventional MD, a result that was not apparent when the albedo effect was not included in the reference LCA (Stratton *et al* 2010). Conversely, renewable MD production from salicornia cultivated on land that was previously desert yields a net warming effect, corresponding to  $228 \text{ gCO}_2\text{e/MJ}$  of MD fuel. This is the first evidence that salicornia-derived biofuel obtained by converting desert land could be potentially detrimental from a climate impact standpoint when compared to conventional fuels. Our results give support for further evaluating the consideration of LUC-induced surface albedo changes in global biofuels policies (Betts 2000, 2001, Claussen *et al* 2001, Bala *et al* 2007).

Some limitations of this study warrant acknowledgment. First, our analysis is restricted to changes in surface albedo, and other biogeophysical impacts such as evapotranspiration, surface roughness and rooting depth are not quantified here. Second, the albedo effects shown in figure 1 are dependent on the sample geographical locations chosen, and should not be interpreted as characteristics of the feedstocks considered, but rather as a function of the biomass feedstock and original land use pairing investigated. Third, the use of equivalent emissions based on RF has a theoretical weakness (Davin *et al* 2007) because albedo effects and biogeochemical effects act on different spatial and temporal scales. Nevertheless, equivalent emissions of  $\text{CO}_2$  per unit energy of combusted fuel is a widely accepted metric used to compare both effects (Betts 2001, Bird *et al* 2008, Georgescu *et al* 2011, Cherubini *et al* 2012). When RF is used to compare different climate change mechanisms, there is an implicit assumption that the climate response is proportional to forcing. However, research by Hansen and Nazarenko (2004) show that surface forcing may be twice as effective at high latitudes as at low latitudes in generating surface temperature change. Further discussion is available in Betts *et al* (2007), Bird *et al* (2008), and in Cherubini *et al* (2013). With respect to time scales, the global RFs (and equivalent  $\text{CO}_2$  emissions) evaluated in this study reflect the impacts of albedo variations averaged over a whole year of LUC in order to compare the albedo effect with the long-term biogeochemical impacts. However, albedo coefficients are dependent upon transient surface conditions (Song 1999), and these variations may lead to significant

seasonal impacts on the local climate. These impacts may be offsetting when averaged over a whole year, as found by Georgescu *et al* (2013) for the biogeophysical effects of savannah to sugarcane conversion. Finally, the albedo impacts of other variables such as snow cover variation due to LUC, and climate-meteorology feedbacks potentially affecting local cloudiness, are not accounted for in this study.

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