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LAND USE IN LCA

Including CO_2-emission equivalence of changes in land surface albedo in life cycle assessment. Methodology and case study on greenhouse agriculture

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Abstract

Purpose Climate change impacts in life cycle assessment (LCA) are usually assessed as the emissions of greenhouse gases expressed with the global warming potential (GWP). However, changes in surface albedo caused by land use change can also contribute to change the Earth's energy budget. In this paper we present a methodology for including in LCA the climatic impacts of land surface albedo changes, measured as CO_2-eq. emissions or emission offsets.

Methods A review of studies calculating radiative forcings and CO_2-equivalence of changes in surface albedo is carried out. A methodology is proposed, and some methodological issues arising from its application are discussed. The methodology is applied in a practical example dealing with greenhouse agriculture in Southern Spain.

Results The results of the case study show that the increase in surface albedo due to the reflective plastic cover of greenhouses involves an important CO_2-eq. emission offset, which reduces the net GWP-100 of tomato production from 303 to 168 kg CO_2-eq. per ton tomato when a 50-year service time is considered for the agricultural activity. This example shows that albedo effects can be very important in a product system when land use plays an important role, and substantial changes in surface albedo are involved.

Conclusions Although the method presented in this work can be improved concerning the calculation of radiative forcing, it constitutes a first operative approach which can be used to develop regionalized characterization factors and provide a more complete evaluation of impacts on the climate change impact category.

Keywords Climate change · Global warming potential (GWP) · Greenhouse agriculture · Land transformation · Land use change · Life cycle impact assessment (LCIA) · Radiative forcing

1 Introduction

Climate change is among the most established impact categories in life cycle assessment (LCA) (Udo de Haes et al. 1999). Currently, impacts of products and services on the global climate can be measured by LCA practitioners with several approaches, such as the global warming potential (GWP; Forster et al. 2007), which measures the radiative forcing per unit of emission of different greenhouse gases. GWP is probably the most generally used method, although other approaches exist which go further in the effects chain, measuring potential consequences on humans and ecosystems (De Schryver et al. 2009; Steen

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1999a, b). A common feature of all approaches is the fact that they only focus on emissions of greenhouse gases. However, anthropogenic changes to the land cover can affect surface albedo and exert a radiative forcing by perturbing the shortwave radiation budget (Ramaswamy et al. 2001). According to the Intergovernmental Panel on Climate Change, in the 1750–2005 period global land cover changes—especially deforestation—have increased the terrestrial albedo, resulting in a radiative forcing (RF) of -0.2 W m^{-2} (Forster et al. 2007). Even though this influence might appear small at the global level (radiative forcing from long-lived greenhouse gases is +2.63 W m^{-2}), in recent years the implications of surface albedo changes have been gaining attention, especially as a climate change mitigation strategy (Hamwey 2007; Ridgwell et al. 2009). For example, a global increase of albedo in urban areas, by means of using reflective building materials, has been estimated to have a cooling effect equivalent to offsetting 44 Gt CO_2 (Akbari et al. 2009). On the other hand, Betts (2000) found that reforestation in high latitudes could be detrimental in terms of climate change mitigation, since the positive forcing induced by forest albedo can offset the negative forcing expected from carbon sequestration.

Inclusion of land use impacts in LCA is also gaining attention, since land as a resource can be especially important in agricultural, forestry, and mining products. Actually, this rising interest can be easily illustrated by the establishment in this journal of a specific "Land use' subject (Milà i Canals 2007). To date, research on land use impacts has been mainly focused on biodiversity and soil quality indicators Milà i Canals et al. (2006), whereas the only link made between land use and climate change corresponds to the alteration of carbon stocks, by such processes as converting forest to agricultural land (Cherubini et al. 2009; Silalertruksa et al. 2009), but no attempt has been made so far to tackle the subject of albedo change in the context of LCA. In this paper we present an approach for LCA to include albedo changes from land cover in the climate change impact category, measuring them as CO_2-eq. emissions. The method presented is tested in a practical example on greenhouse agriculture.

2 Fundamentals and review of existing methods

2.1 Relationship between surface albedo and top-of-atmosphere radiative forcing

The amount of shortwave energy reaching the top of the atmosphere (TOA), averaged over the entire planet, has been estimated as 341 W m^{-2} by Trenberth et al. (2009; Fig. 1). Of this amount, 79 W m^{-2} is reflected back to space due to clouds and aerosols, and 78 W m^{-2} is absorbed by the atmosphere. The remaining 184 W m^{-2} reaches the Earth's surface, where 23 W m^{-2} is reflected to space and 161 W m^{-2} are absorbed. Therefore, the average surface albedo is 23/184=0.13, whereas the TOA albedo is 102/341= 0.3. According to Le Treut et al. (2007), changing the atmospheric and/or the surface albedo constitutes one of the fundamental ways to disturb the radiation balance of the Earth.

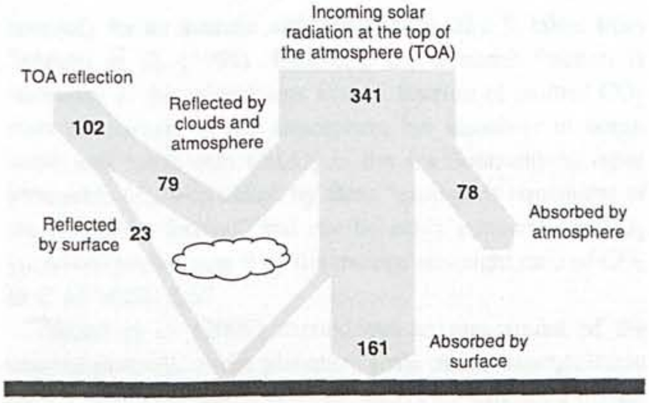

Fig. 1 Global mean shortwave energy flows in watts per square meter. Absorbed incoming shortwave radiation is balanced by releasing the same amount of outgoing longwave radiation. Source: Trenberth et al. (2009)

Ramaswamy et al. (2001) defined RF as the change in net (down minus up) irradiance (solar plus longwave; in watts per square meter) at the tropopause. In broad terms, it describes any imbalance in the planet's radiation budget caused by human interventions. Once RF is applied, the climate system tends to adjust to recover equilibrium, usually by means of changes in temperature (Forster et al. 2007). For most shortwave forcing agents, the instantaneous RF at the TOA is linked to surface temperature change and can be used instead of the stratospheric-adjusted RF at the tropopause (Forster et al. 2007). The instantaneous TOA RF (in watts per square meter) is given by Eq. 1:

$$\mathrm{RF_{TOA}} = -R_{\mathrm{TOA}}\Delta\alpha_{\mathrm{p}} \tag{1}$$

where R_{TOA} is downward solar radiation at the TOA and $\Delta\alpha_{\mathrm{p}}$ is a variation in planetary albedo. R_{TOA} is basically a function of latitude (see Electronic Supplementary Material). Concerning $\Delta\alpha_{\mathrm{p}}$, according to Lenton and Vaughan (2009), changes in surface albedo can be linearly related to changes in α_{p} (Eq. 2):

$$\Delta\alpha_{\mathrm{p}} = f_{\mathrm{a}}\Delta\alpha_{\mathrm{s}} \tag{2}$$

where $\Delta\alpha_{\mathrm{s}}$ is a variation in surface albedo and f_{a} is a parameter accounting for absorption and reflection of solar radiation throughout the atmosphere. Under clear-sky conditions, f_{a} has an approximate global mean value 0.73 (Chen and Ohring, 1985), representative of regions with very low cloud cover, like deserts. On the other hand, lower f_{a} values are representative of cloudy skies. Lenton and Vaughan (2009) estimate f_a for cloudy skies with Eq. 3:

$$f_a = \frac{R_s}{R_{TOA}} T_a \quad (3)$$

where R_s is downward solar radiation at the Earth's surface (in watts per square meter) and T_a is an atmospheric transmittance factor expressing the fraction of the radiation reflected from the surface that reaches the TOA. Using a global value of $T_a = 0.854$ and the global incident radiation at TOA at the Earth's surface, Lenton and Vaughan obtain a global f_a value of 0.48. However, Eq. 3 can be used to calculate site-specific f_a values where R_s is known. As a consequence, combining Eqs. 1, 2, and 3, we can obtain the following expressions to estimate RF_{TOA} as a function of surface albedo changes:

$$RF_{TOA} = -R_s T_a \Delta\alpha_s \quad (4)$$

The method we present in this paper is based on RF_{TOA} estimation using Eq. 4. Nevertheless, in the Electronic Supplementary Material, we show that RF_{TOA} can also be estimated with Eqs. 1 and 2.

2.2 CO_2-equivalence of changes in surface albedo

The concept of RF allows us to compare modifications of the Earth's energy budget exerted by greenhouse gases, with those caused by alterations due to changes in albedo. However, policies like the Kyoto Protocol address climate change mitigation targets in terms of greenhouse gas emission reductions. For this reason, several authors interested in the implications of changes in surface albedo have developed calculation methods to express those changes as CO_2-eq. emissions or emission offsettings.

Betts (2000) developed a methodology aiming to express the forcings from forest sequestration and albedo. Specifically, he aimed at determining the change in terrestrial carbon stock that would be equivalent to a change in surface albedo resulting from a transition from agricultural land to forest land in several regions. He simulated changes in albedo and associated RF and then calculated the change in atmospheric CO_2 concentration (ΔC) which would give the same forcing, by means of Eq. 5, taken from Myhre et al. (1998):

$$RF = 5.35 \ln(1 + \Delta C / C_0) \quad (5)$$

where C_0 is the 1997 global CO_2 concentration. ΔC is converted to a terrestrial carbon stock change ΔC_T by means of Eq. 6:

$$\Delta C_T = 2(M_c / M_a) m_{air} \Delta C / C_0) \quad (6)$$

where M_c and M_a are the molecular masses of carbon and dry air and m_{air} is the mass of the atmosphere. The factor of 2 accounts for an average airborne fraction of 0.5, taken from Schimel et al. (1995). Including the airborne fraction is necessary in the calculations since a fraction of emitted CO_2 does not remain in the atmosphere but dissolves in ocean water and reacts with $CaCO_3$ in the sea floor, among other processes. ΔC_T was called by Betts "emissions equivalent of the shortwave forcing" and can be easily converted to CO_2 emissions multiplying it by the molecular weight ratio of CO_2 to C of 44/12=3.67.

Akbari et al. (2009) carried out an assessment of the cooling potential at the planetary scale of increasing albedo by 0.1 in urban areas. They estimated CO_2-emission offsets by first calculating with Eq. 5 the RF of a marginal increase of 0.128 ppmv in atmospheric CO_2, resulting in a forcing of +0.91 W kg CO_2^{-1}. They calculated that a 0.01 increase in the Earth's surface albedo exerts a mean global forcing of -1.27 W m^{-2}. With these data, they concluded that increasing albedo by 0.01 is equivalent to offsetting 1.27/0.91=1.4 kg CO_2 m^{-2}. However, this figure refers to changes in atmospheric CO_2. Similarly to Betts (2000), they consider an average CO_2 airborne fraction of 0.55 (Denman et al. 2007); thus, the emission offset is 1.4/0.55= 2.55 kg CO_2 m^{-2} when surface albedo is increased by 0.01.

Bird et al. (2008) attempted to model the climate change effects of afforestation/reforestation projects, by comparing the RF due to carbon sequestration and to changes in land use from grasslands to forest in various locations and forest types in Canada. Both effects were expressed as CO_2-eq. emissions. They developed a set of equations describing changes in TOA albedo, radiative forcing, and CO_2 equivalence of albedo change. This method differs from that by Akbari et al. (2009) in the fact that local incident radiation is used instead of global values, thus discriminating the CO_2 equivalence of albedo change in different locations. Another difference of this approach with regard to Akbari et al. (2009) and Betts (2000) is the conversion of atmospheric CO_2 to emitted CO_2, by the so-called airborne fraction. As we have seen, Akbari et al. (2009) and Betts (2000) deal with this by taking into account an average airborne fraction of 0.55 and 0.5, respectively. These figures are based on the observed constant relationship between global CO_2 emissions and atmospheric concentration since 1958 (Schimel et al. 1995; Denman et al. 2007). On the other hand, Bird et al. (2008) do not take into account in their model a fixed airborne fraction, but a time-dependent relationship. This is justified by the fact that the airborne fraction of an instantaneous release of CO_2 decays over time. For relatively small perturbations, it can be approximated from the Bern carbon cycle model (Joos et al. 2001):

$$f(t) = 0.217 + 0.259e^{-\Delta t/172.9} + 0.338e^{-\Delta t/18.51} + 0.186e^{-\Delta t/1.186} \quad (7)$$

According to this model, after 10 years 66% of the initial emission remains in the atmosphere, while only 36% remains after 100 years. As a consequence, the choice of a time horizon affects the magnitude of the CO_2-eq. emissions. For a time horizon of 100 years, usually used in the calculation of GWP, the average airborne fraction, calculated as the integral of Eq. 7 from year 0 to 99, is 0.48, quite close to those used by Betts (2000) and Akbari et al. (2009).

3 Determination of the radiative parameters

3.1 Downward solar radiation at the Earth's surface

For a particular site, average annual R_s can be either experimentally measured with a pyranometer for a representative period of time or calculated from available statistics from the closest meteorological station. It is also possible to take advantage of existing tools and databases which have been developed to determine this parameter for the assessment of solar energy potential in different regions. An example of this is the Photovoltaic Geographical Information System (EC 2008).

3.2 Surface albedo

We can distinguish between empirical and modeling approaches for the determination of α_s. Empirical approaches include remote sensing and field measurements. Concerning remote sensing, data from the Moderate Resolution Imaging Spectrometer (MODIS) are particularly useful. MODIS is a radiometer operated aboard the NASA Earth Observing System Terra and Aqua spacecrafts. It collects data over a broad spectral range from the visible to longwave infrared (Xiong et al. 2009). MODIS provides measurements of instantaneous land surface reflectivity, and daily mean and annual averages must be estimated from representative data series. However, MODIS data have a resolution of 500 m; hence, when the focus is on small land parcels, field measurements are preferred. The latter can be made by means of an albedometer, which essentially consists of a combination of two pyranometers, one facing upward and one facing downward.

Changes in surface albedo can also be estimated by means of modeling techniques. Yin (1998) proposed a model for the analysis and projection of albedo in vegetated land surfaces. Models for simulation of albedo in urban areas have also been developed, such as that by Chimklai et al. (2004), taking into account the building height distribution, solar positions, the effects of multiple reflections and shading. Comprehensive overviews of albedo for various vegetation types, land covers, and materials were published by Kondratyev (1969, 1972), Iqbal (1983), Gates (1980), and Breuer et al. (2003).

4 A framework for considering surface albedo changes in LCA

A special feature of LCA as an environmental assessment tool is the fact that it focuses on product systems, the environmental burdens of which are allocated to so-called functional units, representing a quantitative measure of the function delivered by the product system. As a consequence, CO_2-eq. emissions from surface albedo changes need to be attributed to a product system and functional unit. Figure 2 shows a simplified representation of albedo changes in land cover albedo for two product systems P_1 and P_2 with two land use types, LU_1 and LU_2, which have surface albedo values α_{sLU1} and α_{sLU2}, respectively, where $\alpha_{sLU1} < \alpha_{sLU2}$. For simplicity, we assume albedo to be constant in each type of use. It is important to highlight at this point the difference between land occupation and land transformation: Land occupation refers to using a land area during a certain amount of time, assuming no transformation of the land properties during this use (Lindeijer et al. 2002; Milà i Canals et al. 2007a); land occupation is measured as the product of surface and time (square meter year). In Fig. 1 land occupation for P_1 starts at t_1 and finishes at t_2. On the other hand, land transformation implies changing the properties of a land area according to the requirements of a given new type of use (Lindeijer et al. 2002; Milà i Canals et al. 2007a); land transformation is measured in surface units (square meter). In Fig. 2 there is a land transformation process when P_1 starts and a new one when P_2 starts. Radiative forcings exerted by changes in albedo are related to land transformation rather than to land occupation. In Fig. 2 when LU_1 is changed to LU_2, albedo

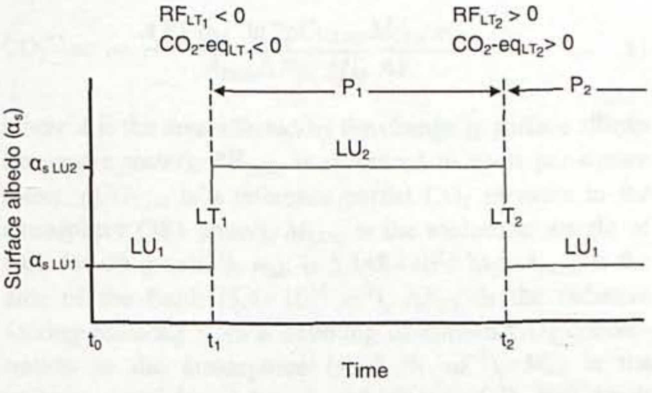

Fig. 2 Conceptual representation of surface albedo change in two product systems. *LU* land use, *LT* land transformation, *RF* radiative forcing, *P* product system, *CO_2-eq.* carbon dioxide equivalent emissions

increases, inducing a negative RF that can be expressed as a CO_2-eq. emission offset. It must be stressed that this offset is a result of changing the albedo, regardless of the duration of LU_2. Subsequently, when activity P_1 finishes and P_2 starts we have again a land transformation, from LU_2 to LU_1, inducing a positive RF that can be expressed as a CO_2-eq. emission. Assuming that P_1 and P_2 use the same amount of land, then the CO_2-eq. offset by the start of P_1 and the CO_2-eq. emission by the start of P_2 counterbalance each other.

This example raises at least two methodological questions concerning how to allocate CO_2-eq. from changes in surface albedo in LCA studies: (1) allocation to a given product system and (2) allocation to a functional unit.

4.1 Allocation to a product system

As we have seen from the example in Fig. 2, P_1 involves transforming the land to a more reflective type of land cover, and this can be expressed as a CO_2-eq. emission saving, analogous to a carbon sequestration. However, when the activity of P_1 finishes, land is changed again by P_2 to its original state before P_1 so that the environmental achievement by P_1 is canceled. The question here is if P_1 should then be allocated a CO_2-eq. offset. If we analyze Fig. 2 with a focus on land as a whole system in the t_2–t_0 period, the net environmental benefit is zero. However, LCA deals with product systems; thus, there is a need to allocate transformation interventions in Fig. 2 to P_1 and P_2. Using causality as guiding principle, we suggest that land transformed by a use of the land for new purposes should be attributed to this future new use. In such a case, P_1 should receive an environmental credit due to the increase in surface albedo from $\alpha_{s\ LU1}$ to α_{sLU2}, whereas P_2 should receive an environmental burden caused by decreasing surface albedo from α_{sLU2} to α_{sLU1}. This allocation principle is in accordance with current practice in the LCI database ecoinvent (Frischknecht and Jungbluth 2007).

4.2 Allocation to a functional unit

The second question is how to allocate a CO_2-eq. emission or emission offset within a product system to a functional unit. Changes in albedo are attributed to land transformation; hence, they constitute one-time interventions, just as manufacturing capital equipment (machinery, buildings) or clearing a forest before an agricultural activity. The only way of allocating one-time interventions to a functional unit is to assume an expected lifetime for the affected activity, which can be uncertain. In economics, for instance, this is dealt with by means of the depreciation concept. The subject of one-time interventions or preparatory processes in the context of land use in LCA has already been debated in the past (see Udo de Haes 2006; Milà i Canals et al. 2007b). The problem of allocating climate burdens from land transformation to a functional unit is not different from, for instance, allocating the manufacture of a tractor to an agricultural product. As Milà i Canals et al. (2007b) point out, there is no scientific way to predict the future of markets, and a "clear" allocation of preparative interventions to the future years of the created structure has to be based on societal agreements to avoid arbitrariness. As they also point out, an exclusion of preparatory processes from LCA, due to their less direct allocability to the product or service, would seriously jeopardize the usability of LCA as a decision tool. The latter is supported by Frischknecht et al. (2007) who assessed the influence of capital goods in the environmental profile of hundreds of datasets from the ecoinvent database. This does not necessarily mean that changes in surface albedo have the same influence in LCA studies than capital goods, but we want to stress the fact that they do not involve a particularly special type of allocation problem. Some examples of how land use change can be dealt with are provided by the carbon footprinting methodology according to the British PAS 2050 standard (BSI 2008) and by the European Directive on energy from renewable sources (European Union 2009), in which emissions from land use change must be taken into account, distributing them over the functional unit during the first 20 years after land was changed.

4.3 Mathematical expression for CO_2-equivalence of changes in surface albedo and characterization factors

The derivation of a general expression for CO_2-eq. emissions from surface albedo changes is based on previous work by Bird et al. (2008). The reader is referred to that work for further details. Based on Betts (2000), Bird et al. (2008) express CO_2-eq. emissions (in grams) from surface albedo changes as

$$CO_2-\text{eq.} = \frac{A\,\mathrm{RF_{TOA}}\ \ln 2\mathrm{pCo_{2,ref}} M_{\mathrm{CO_2}}\ m_{\mathrm{air}}}{A_{\mathrm{Earth}} \Delta F_{2X}\, M_{\mathrm{air}}\ \mathrm{AF}} \tag{8}$$

where A is the area affected by the change in surface albedo (in square meter), $\mathrm{RF_{TOA}}$ is measured in watts per square meter, $\mathrm{pCO_{2,ref}}$ is a reference partial CO_2 pressure in the atmosphere (383 ppmv), M_{CO2} is the molecular weight of CO_2 (44.01 g $\mathrm{mol^{-1}}$), m_{air} is 5.148×10^{15} Mg, A_{Earth} is the area of the Earth (5.1×10^{14} $\mathrm{m^2}$), ΔF_{2X} is the radiative forcing resulting from a doubling of current CO_2 concentration in the atmosphere (+3.7 W $\mathrm{m^{-2}}$), M_{air} is the molecular weight of dry air (28.95 g $\mathrm{mol^{-1}}$), and AF is the average CO_2 airborne fraction. All the variables taking constant values in Eq. 8 can be grouped in a single parameter, the value of which is 1,101 W g CO_2^{-1}. The inverse of this constant is the marginal RF of CO_2 emissions at the current atmospheric concentration, which we will express in kilograms (0.908 W kg CO_2^{-1}). Substituting in Eq. 8, we obtain Eq. 9:

$$\mathrm{CO_2{-}eq.} = \frac{A\,\mathrm{RF_{TOA}}}{\mathrm{RF_{CO_2}}\,\mathrm{AF}} \tag{9}$$

In this equation, CO_2-eq. emissions are expressed in kilograms. Now we call A as the land transformation per functional unit (LT_{FU}) and substitute RF_{TOA} by means of Eq. 4:

$$\mathrm{CO_2{-}eq.} = \frac{\mathrm{LT_{FU}}\,R_\mathrm{s}\,T_\mathrm{a}\Delta\alpha_\mathrm{s}}{\mathrm{RF_{CO_2}}\,\mathrm{AF}} \tag{10}$$

Substituting $\Delta\alpha_s$ by an initial and final surface albedo values, α_{sLU1} and α_{sLU2}, we finally obtain Eq. 11:

$$\mathrm{CO_2{-}eq.} = \frac{\mathrm{LT_{FU}}\,R_\mathrm{s}\,T_\mathrm{a}(\alpha_\mathrm{sLU1} - \alpha_\mathrm{sLU2})}{\mathrm{RF_{CO_2}}\mathrm{AF}} \tag{11}$$

The average AF is a function of time, since the airborne fraction of an instantaneous release of CO_2 decays over time. Given a time horizon of n years, AF is calculated with Eq. 12, where $f(t)$ is the Bern carbon cycle model (Eq. 7):

$$\mathrm{AF} = \frac{\int_1^n f(t)\mathrm{d}t}{n} \tag{12}$$

Equation 12 gives AF values of 0.69, 0.48, and 0.32 for the usual time horizons considered in GWP of 20, 100, and 500 years, respectively.

From Eq. 11 we can derive characterization factors (ChF, in kilograms CO_2-eq. per square meter) for the initial and final land uses, respectively:

$$\mathrm{ChF_{LU1}} = +\frac{R_\mathrm{s}\,T_\mathrm{a}\alpha_\mathrm{sLU1}}{\mathrm{RF_{CO_2}}\,\mathrm{AF}} \tag{13}$$

$$\mathrm{ChF_{LU2}} = -\frac{R_\mathrm{s}\,T_\mathrm{a}\alpha_\mathrm{sLU2}}{\mathrm{RF_{CO_2}}\,\mathrm{AF}} \tag{14}$$

Positive and negative signs in Eqs. 11, 13, and 14 are used in such a way that negative CO_2-eq. emissions are obtained when albedo is increased, and vice versa. As it can be seen, characterization factors, besides being albedo-dependent, allow the user to define specific values for locations receiving different solar radiation levels, as well as for different time horizons. It must also be highlighted that this approach can be used either for land transformations taking place in the foreground system as well as for those related to the background system, provided that the background data include land transformation interventions.

4.4 Uncertainty

The uncertainty in these calculations depend on the respective uncertainties of the user-defined data (LT_{FU}, α_{sLU1}, α_{sLU2}, and R_s) and of the default values for T_a, RF_{CO2}, and AF. An approximate error of ±30% is associated with T_a, based on the range of values suggested by Lenton and Vaughan (2009), whereas for RF_{CO2} Akbari et al. (2009) suggest a ±10% error. Concerning AF, the error is less than ±15% (Forster et al. 2007, p. 211). Thus, an overall error for CO_2-eq. emissions around ±35% should be expected, excluding the contribution from user-defined parameters. The uncertainty of LT_{FU} will be associated with that of the inventory data used but also with the definition of a service life for the activity under study, as discussed in Section 4.2. On the other hand, R_s can be quantified with a low level of error, either with measurements or with models. With regard to initial and final albedo, substantial uncertainty can be expected if the values used do not come from measurements; otherwise, they should be substantially lower. In the following section, the overall uncertainty of the CO_2-eq. emissions calculation is provided for plastic greenhouses in Almería.

5 Case study: horticultural production in Almería

As an example of application, a cradle-to-gate LCA of intensive tomato production in the province of Almería (southeastern Spain) is carried out. This region has experienced from the 1970s a rapid development of greenhouse horticulture. According to Sanjuan (2007), almost 26,000 ha of land were covered by plastic greenhouses in 2007, and they currently increase at an average rate of 500 ha year^{-1}. The study focuses only on the climate change impact category, using GWP-100 as characterization model, taking into account carbon from both biogenic and fossil sources. Nevertheless, values for GWP-20 and GWP-500 are also calculated as a sensitivity analysis.

5.1 Inventory for the farming activity

Unfortunately, there are no published LCA studies for tomato production in Almería. As a consequence, most of the data used corresponds to the same process in Barcelona (Antón et al. 2005), with a similar climate to that of Almería. It is assumed for this example that the amount of inputs to the farm in Barcelona is comparable to those in Almería. Nevertheless, some processes related to soil preparation, greenhouse maintenance, and water pumping are taken from a study in this region (Muñoz et al. 2009). The following processes are included in the inventory: change in biomass carbon stocks due to clearing of land prior to the agricultural activity, greenhouse infrastructure production, maintenance and disposal, soil preparation, carbon fixation by the crop, fertilizers production and N_2O emissions from their application, water pumping, transport, and treatment of green waste. Soil CO_2 emissions due to changes in soil organic matter during the farming period are not included due to lack of data. This can be considered as an important limitation of this case study, since these emissions have been found to be of the outmost importance in agricultural systems (Koerber et al. 2009; Brandão et al. 2010). As background data, the ecoinvent 2.0 database has been used (Swiss Centre for Life Cycle Inventories 2008). Production of pesticides has been excluded from the study, since their contribution outside toxicity-related impact categories is very low (Antón et al. 2005). The detailed inventory data for the farming activity are shown in the Electronic Supplementary Material.

5.2 Calculation of CO_2-eq. emissions from surface albedo change

The calculation is made using the following data: The tomato yield considered is 12 kg m^{-2} $year^{-1}$ (Antón 2004); therefore, land occupation is 83 m^2 year t^{-1}. As already discussed, the CO_2 equivalence of albedo change is related to land transformation. As a consequence, a time span for the farming activity has to be defined. For this example we choose a period of 50 years, resulting in a LT_{FU} of 1.67 m^2 t^{-1}. The annual mean incident solar radiation (R_s) in this area is 196 W m^{-2} for the 2001–2005 period, according to Campra et al. (2008). Concerning the surface albedo values, a mean annual value of 0.19±0.02 was observed for the replaced grassland and 0.4±0.06 for an area fully covered by greenhouses (Campra et al. 2008). If we use Eq. 15 with AF for 100 years, the resulting GWP-100 is −134 kg CO_2-eq. per ton tomato. The corresponding results for GWP-20 and GWP-500 can be also calculated as in Eq. 11, replacing 0.48 by 0.69 and 0.32, respectively.

$$\begin{aligned} CO_2-\text{eq.} &= \frac{1.67 \times 196 \times 0.854 \times (0.19-0.40)}{0.908 \times 0.48} \\ &= -134\,\text{kg}\,CO_2-\text{eq.ton}^{-1} \qquad (15) \end{aligned}$$

The uncertainty involved in this calculation, excluding the contribution from LT_{FU}, is up to ±45%. The contribution of R_s to this uncertainty is not included either, although it is considered to be very small, given that the value used comes from field measurements with a pyranometer (Campra et al. 2008).

6 Results and discussion

In Table 1 the CO_2-eq. emissions associated to the cradle-to-gate farming activities are summarized. As it can be seen, the GWP-100 is 303 kg CO_2-eq. per ton tomato, which is reduced to 168 kg CO_2-eq. per ton tomato if the change in surface albedo is taken into account. The choice of time horizon in the GWP affects the magnitude of the albedo effect, being increased with longer time horizons such as 500 years. These results show that the local radiative forcing caused by the land cover change has a remarkable offset effect on the overall greenhouse gas balance of this particular product system, equivalent to 44% of its emissions when GWP-100 is considered. Campra et al. (2008) showed the first empirical evidence to support that changes in surface albedo caused by the highly reflective plastic cover in this area have led to a cooling trend in surface temperature. However, the magnitude of this effect, when measured as CO_2-eq. emissions per unit product, depends on the choice of a service lifetime, which in this example was taken as 50 years. The emission offset increases for shorter lifetimes, for example it increases from 134 to 269 kg CO_2-eq. per ton tomato when a 25-year lifetime is considered but decreases to 67 kg CO_2-eq. per ton tomato when it is expanded to 100 years. Therefore, when the implications of changes in albedo are of such high magnitude as in the system under study, the choice of this lifetime is of the utmost importance. Nevertheless, it should not always be expected that changes in albedo have such a high influence in LCA studies. The example shown is a very particular case in which a sharp increase in surface albedo is caused by white greenhouses. Another particular case where albedo could have an important influence in the CO_2-eq. emission balance is in the context of forestry or any other system involving land use in high latitudes, where long-lasting snow cover is affected in some way (Betts 2000) or anywhere where the reflectance of land cover materials is changed on purpose, as is the case of buildings and urban areas (Akbari et al. 2009). These are examples of product systems where land use plays a significant role; in product systems where land use is only a background issue, the influence of changes in surface albedo is expected to be less important than that from emissions of greenhouse gases.

Nonetheless, the presented method can be used to assess both interventions in the foreground and the background systems. In the latter case, a set of characterization factors should be developed for different land use classes, although a certain level of regionalization is needed due to several reasons: The first is that characterization factors depend on the local intensity of solar radiation, and the second is the effect of snow: Even though a coniferous forest may have a similar summer albedo in different locations, the presence or absence of snow in winter would make a substantial difference in the annual mean albedo for locations in, for instance, southern and northern Europe. Regionalized impact assessment methods have already been developed

Table 1 GWP (kilogram CO_2-eq.) for growing 1,000 kg tomatoes

Process	GWP-20	GWP-100	GWP-500
Change in biomass carbon stock[a]	2	2	2
Carbon fixation by crop[a]	−190	−190	−190
Greenhouse infrastructure	283	226	204
Soil preparation	6	6	6
Greenhouse maintenance	<1	<1	<1
Fertilizers	94	93	65
N_2O emissions	55	57	29
Greenhouse disposal	6	3	2
Water pumping	24	22	21
Green waste treatment[b]	83	84	83
Overall emissions (*a*)	365	303	223
Change in surface albedo (*b*)	−93	−134	−202
Net with albedo change ($c=a+b$)	272	168	21
Ratio (*c*) to (*a*)	75%	56%	9%

[a] Biogenic CO_2

[b] Mostly biogenic CO_2

for other well-established impact categories like acidification and eutrophication (Huijbregts et al. 2000), but this is the first time that such a need is identified for climate change, an impact category with site-independent characterization factors. While greenhouse gases are assumed to be well mixed and distributed in the atmosphere, regardless of where they are emitted, changes in albedo involve effects on the climate at a regional–local scale, in the area where solar energy budget is changed.

This method constitutes a simple analytical approach to assess the climate burdens from changes in land surface albedo. Besides the allocation problems discussed in Section 3, it has other limitations, such as the uncertainty involved. In the presented case study, the calculations are estimated to have an uncertainty of up to ±45%. Among the most important factors contributing to this uncertainty is the simple modeling of atmospheric transmittance (T_a). Further refinement of this parameter would require a more sophisticated modeling, which should include local data on cloud cover, as provided for example by the International Satellite Cloud Climatology Project (ISCCPD2). Another limitation is the need to obtain local data on surface albedos, either by means of field measurements or remote sensing. Although it might be tempting to use literature albedo values, it must be stressed that the CO_2-eq. emissions are very sensitive to small changes in albedo, and general albedo values in the literature are sometimes given as ranges with rather broad limits. For instance, according to Taha et al. (1988) albedo for crops is in the 0.15–0.25 range, whereas for urban areas, it can be anything from 0.1 to 0.35. Finally, it is also important to consider that RF and hence the GWP metric itself have their limitations (see Forster et al. 2007, pp. 210–211), especially when the focus is on climate impacts from land use change. For example, deforestation in the tropics decreases evapotranspiration rates and increases sensible heat fluxes, resulting in regionally decreased precipitation and increased surface temperature (Bala et al. 2007). These kinds of effects cannot be quantified in terms of radiative forcing nor, therefore, as GWP either. Some authors have proposed new metrics to quantify land use disturbances on the climate, such as the Regional Climate Change Potential by Pielke et al. (2002). Nevertheless, direct comparison of land cover change effects with greenhouse gas emissions remains a challenge.

7 Conclusions

A method has been introduced to include in LCA studies the radiative forcing exerted by changes in land surface albedo, expressed as CO_2-eq. emissions. This method uses a simple analytical approach, based on previous work in the field of climate geoengineering. Besides enabling the assessment of foreground interventions on land, it can also be used to assess background interventions, although this will require the development of regionalized characterization factors. A practical example of intensive tomato cultivation under reflective plastic greenhouses in southern Spain has shown that the effect of surface albedo changes can have a very important influence in the climate change impact category, provided that (1) land use plays an important role in the system (such as in agriculture, forestry and mining, buildings, and urban areas) and (2) substantial changes in surface albedo are expected in the product system.

This method raises some methodological problems in the context of LCA, which have also been discussed. They are related to the fact that the CO_2-eq. emissions associated to changes in surface albedo are a consequence of land transformation, not of land occupation. As a consequence, these emissions are one-time interventions which have to be allocated to the functional unit by means of an expected service lifetime. Another problem arising from the land transformation dependency is the fact that impacts are reversible: If in the same product system albedo is changed but returned to its final state at the end of the service lifetime, the net albedo change, and thus, the CO_2-eq. emissions are zero. These methodological problems are analogous to those from accounting changes in carbon stocks in LCA.

Although the method presented can be improved concerning the calculation of radiative forcing, it constitutes a first operative approach for LCA to go beyond greenhouse gas accounting and provide a more complete evaluation of human contributions to climate change.

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