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Quantifying the climate change effects of bioenergy systems: Comparison of 15 impact assessment methods

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Abstract

Ongoing concern over climate change has led to interest in replacing fossil energy with bioenergy. There are different approaches to quantitatively estimate the climate change effects of bioenergy systems. In the present work, we have focused on a range of published impact assessment methods that vary due to conceptual differences in the treatment of biogenic carbon fluxes, the type of climate change impacts they address and differences in time horizon and time preference. Specifically, this paper reviews fifteen different methods and applies these to three hypothetical bioenergy case studies: (a) woody biomass grown on previously forested land; (b) woody biomass grown on previous pasture land; and (b) annual energy crop grown on previously cropped land. Our analysis shows that the choice of method can have an important influence on the quantification of climate change effects of bioenergy, particularly when a mature forest is converted to bioenergy use as it involves a substantial reduction in biomass carbon stocks. Results are more uniform in other case studies. In general, results are more sensitive to specific impact assessment methods when they involve both emissions and removals at different points in time, such as for forest bioenergy, but have a much smaller influence on agricultural bioenergy systems grown on land previously used for pasture or annual cropping. The development of effective policies for climate change mitigation through renewable energy use requires consistent and accurate approaches to identification of bioenergy systems that can result in climate change mitigation. The use of different methods for the same purpose: estimating the climate change effects of bioenergy systems, can lead to confusing and contradictory conclusions. A full interpretation of the results generated with different methods must be based on an understanding that the different methods focus on different aspects of climate change and represent different time preferences.

1 | INTRODUCTION

The continued increase in CO_2 concentration in the atmosphere has led to concerns about climate change impacts on nature and human societies. Hence, many governments and companies are taking action to curb CO_2 emissions. In its fifth assessment report, the IPCC identified that bioenergy can play a critical role in climate change mitigation, as part of the low-carbon renewable energy mix required to reduce greenhouse gas (GHG) emissions (IPCC, 2014). Bioenergy can be produced from woody crops on short or long rotations, from annual crops such as corn, wheat or sugar cane, or from various organic residues. It may be used in a range of ways, including in solid form to supply heat or electricity, or as a liquid transport fuel (Creutzig et al., 2015). Globally, biomass is the most significant non-fossil source of energy. Biomass supplies about 10% of global energy needs (IEA, 2017), and various policy initiatives in a number of countries aim to further bolster that contribution.

Bioenergy systems vary widely, in terms of the crop type (sugar, starch, vegetable oil, grass, lignocellulosic) and the land-use system that supports it (cropping, forestry), as well as the conversion technology (combustion, pyrolysis, fermentation, transesterification, etc.) and final energy product produced (bioethanol, biodiesel, electricity, heat). There is also significant variability in the specific agroclimatic conditions in which the crops are grown and the subsequent links in the value chain (e.g., processing and transport). Inherently, these differences lead to a wide range of results for climate change effects of bioenergy systems (Creutzig et al., 2015). Results also vary because of the methodological choices adopted in the modelling of different systems (Brandão & Cowie, 2015; Chum, Faaij, Moreira, & Junginger, 2011; Lamers & Junginger, 2013; de Rosa, Pizzol, & Schmidt, 2018).

A systematic approach based on Life-cycle assessment (LCA) has shown that the climate assessed mitigation potential of bioenergy systems depends on a range of methodological choices (Breton, Blanchet, Amor, Beauregard, & Chang, 2018; Cherubini et al., 2009; Helin, Sokka, Soimakallio, Pingoud, & Pajula, 2013; Lamers & Junginger, 2013; Røyne, Peñaloza, Sandin, Berlin, & Svanström, 2016), such as selection of reference land uses (Koponen, Soimakallio, Kline, Cowie, & Brandao, 2018), system modelling approach (attributional or consequential, which determines which activities are included within the system boundary, including indirect land-use change) and impact assessment method. These methodological choices and assumptions have led to a wide divergence among published studies assessing the effectiveness of bioenergy for climate change mitigation (Brandão & Cowie, 2015; Zanchi, Pena, & Bird, 2012). One aspect that has received only scant attention in the past is the sensitivity of climate impact results to the impact assessment method applied (Breton et al., 2018; Helin et al., 2013; Levasseur et al., 2016; Plattner, Stocker, Midgley, & Tignor, 2009; Røyne et al., 2016), and the present paper focuses on that aspect.

1.1 | Impact assessment methods for assessing climate change effects of GHG fluxes

The climate change mitigation value of bioenergy ultimately rests on its ability to deliver end-use energy with lower climate impacts than its fossil energy counterparts. However, the climate system response varies over time and space (Zanchi et al., 2012), and there is not a single indicator that can capture this variability (Allen et al., 2016; Cherubini, Fuglestvedt, et al., 2016). A variety of methods have therefore been devised that take different approaches to quantifying various aspects of climate change (Helin et al., 2013; Levasseur et al., 2016; Plattner et al., 2009).

Impact assessment methods are surrogate measures for quantifying the climate change effects of an activity or product. They express relationships between variables, such as between CO_2 emissions and radiative forcing. They are used to implicitly relate easily quantifiable physical perturbations (e.g., carbon stock changes) to some facet of climate change impacts (e.g., temperature change). Impact assessment methods thus use various tractable biophysical effects, deemed to relate to ultimate impacts, to derive values that consumers or policymakers can use to compare and choose between, different options. All impact assessment methods should be underlain by a transparent theory that relates the method to ultimate climate change impacts.

Several different approaches have been used to quantify climate change impacts in the assessment of bioenergy systems. Different impact assessment methods represent different mid-point or endpoint impacts in the cause-effect chain (e.g., carbon stock changes, cumulative radiative forcing or various aspects of temperature changes). Some of these impact assessment methods deal explicitly with the effect of timing of GHG emissions and credit delayed emissions or temporary carbon sequestration and storage in different ways (Lamers & Junginger, 2013; Levasseur et al., 2016; de Rosa et al., 2018; Røyne et al., 2016).

This paper summarizes 15 different climate change impact assessment methods and presents a comparison of the results obtained when applying these impact assessment methods to three simplified bioenergy systems that differ in the timing and magnitude of emissions and removals. For some impact assessment methods, we also show the results of constituent components for the method (Climate Change Impact Potentials) or illustrate it with different parameter values (O'Hare) or present two interpretations of the same method (Moura-Costa).

1.2 | Summary of climate change impact assessment methods

In this section, we give a brief description of each of the 15 methods applied. These descriptions are complemented by the respective mathematical expressions given in the Supporting Information (Appendix S1) that details the application of these methods to the simplified bioenergy systems. These 15 methods were originally devised to assess: (a) relative climate effects of different GHGs (100-year integrated radiative forcing using GWPs, Temperature changes at year 100 using GTPs); (b) credits from temporary carbon storage in land-use projects (Moura-Costa, Lashof); (c) climate effects due to changes in terrestrial carbon stocks (Average C stock approach, Müller-Wenk and Brandão, C balance indicator); (d) temporally distributed emissions in LCA and carbon footprinting (Clift and Brandão, ILCD, TAWP, Dynamic LCA, GWP_{bio}, CTP, O'Hare); and endpoints (CCIP).

1.2.1 | 100-Year integrated radiative forcing using GWPs

The Global Warming Potential (GWP) is defined as the time-integrated radiative forcing due to a pulse emission of a given GHG, relative to the pulse emission of an equal mass of CO_2 (Myhre, Shindell, & Bréon, 2013). Radiative forcing decreases over time in line with the decrease in atmospheric CO_2 concentration caused by CO_2 uptake by the oceans and biosphere. For our calculations of the GWP and other impact assessment methods discussed below that also use the decay curve of atmospheric CO_2, we used the most recent reparameterization resulting from the multi-model analysis performed by Joos et al. (2013). GWP thus quantifies the total energy added to the climate system by a pulse emission of the added GHG. It is the default method recommended by the International Organisation for Standardization for carbon footprinting (ISO, 2013).

In our calculation here, we assigned a GWP of 1 to all carbon dioxide emissions (fossil or biogenic) and −1 to CO_2 sequestration, regardless of the timing of their occurrence (the GWP value for CO_2 is, by definition, always 1 irrespective of the time horizon, for example, 20, 100, 500 years). In the present work, we focus only on carbon dynamics and do not consider the effects of other GHGs. It is noteworthy that GWPs are calculated based on cumulative radiative forcing over 100 years from the time of emission, thereby applying a sliding window, implying that this method gives equal weight to an emission whenever it occurs.

1.2.2 | Temperature changes at year 100

The Global Temperature change Potential (GTP) has also been presented by the IPCC. It quantifies the effect of GHG emissions on the global temperature at a specified future time (Myhre et al., 2013; Shine, Fuglestvedt, Hailemariam, & Stuber, 2005). Temperature change is thus one step further along the cause-effect chain than radiative forcing, and is, thereby, more closely related to ultimate climate change impacts. However, that also introduces a higher degree of calculation uncertainty related to the details of calculating future temperatures. It also raises the fundamental question of whether the temperature experienced on one particular date in the future is an adequate measure of climate change impacts, or whether other temperature-related functions might also be important in reflecting climatic impacts. As opposed to the method above (100-year Integrated Radiative Forcing using GWPs), we used a fixed window for the impact assessment period, that is, we did not use the time-independent factors (GTPs). Temperature changes resulting from forest carbon stock changes are treated identically to those resulting from fossil fuel substitution. GTPs have been calculated here based on the original concepts of the assessment method. Details of those calculations are given in Supporting information (Appendix S1).

1.2.3 | Moura-Costa

In the IPCC special report on Land Use, Land-Use Change and Forestry (IPCC, 2000), two tonne-year approaches were presented that specifically aimed to account for the climate benefits of temporary carbon storage. The first of those, the Moura-Costa method (Moura Costa & Wilson, 2000), sets out an approach to calculate an equivalency factor between cumulative radiative forcing and temporary carbon storage. The integral of the CO_2 decay curve (Joos et al., 2013) of a pulse emission of 1 tCO_2 over 100 years is 52.4 tonne-years. The Moura-Costa method assumes that sequestering and storing one tonne of carbon dioxide for 52.4 years (or 52.4 tCO_2 over 1 year) and then emitting it back to the atmosphere provides a climate benefit equivalent to avoiding the emission of one tonne of fossil CO_2 (i.e., −1 tCO_2).

This can then be used to determine the effects of temporary carbon storage as –0.019 tCO_2 (=1/52.4) per CO_2 tonne-year of actual storage. The equivalence factor of 0.019 is then used to quantify the benefits associated with sequestration and temporary storage. This method calculates a credit for sequestered carbon of less than or equal to 100% of its actual radiative forcing. If the storage period exceeds 52.4 years, credits are capped at 100% (Brandão, 2012).

Further, there are two possible interpretations of this method: (a) in the original interpretation (Noble, Apps, & Houghton, 2000), the calculated credit was applied only for additional carbon sequestered by the project, (e.g., a reforestation project); and (b) in a more recent interpretation (Brandão et al., 2013), the carbon flow is weighted relative to its timing: the further from the beginning of the time horizon, the larger the deduction incurred (of around 2% per year). This deduction is applied equally to all net emissions, including those of carbon already present in the terrestrial ecosystem at the commencement of a project. The latter interpretation, therefore, applies the credit also for delayed emissions. We have applied both approaches to our case studies, denoted as Moura-Costa-1 and Moura-Costa-2. Credits from fossil fuel substitution are independent from the timing of their occurrence in Moura-Costa-1 but not in Moura-Costa-2.

1.2.4 | Lashof

Like the Moura-Costa method, the Lashof method (Fearnside, Lashof, & Moura-Costa, 2000) provides a way of assessing the benefits of carbon storage in terms of tonne-years, but it uses a different basic concept. This method assesses the impact of temporary carbon storage by considering it to be equivalent to delaying a CO_2 emission until the end of the period over which biospheric carbon is stored. It equates the benefits of temporary carbon storage with the radiative forcing that is avoided over the assessment horizon.

The method integrates the CO_2 decay curve (Joos et al., 2013) over the assessment horizon to give cumulative forcing in tonne-years. As mentioned above, the integral is 52.4 tonne-years over 100 years. To assess the benefits of carbon storage for a period of time, the curve is shifted such that the emission is delayed by the corresponding number of years in storage. The portion of the curve that shifts beyond 100 years is no longer considered, and the area under this portion of the curve corresponds to the assumed benefits associated with delaying the emission (or storing carbon). Delaying the emission of 1 tCO_2 by 1 year reduces cumulative forcing over 100 years by 0.4 tonne-years, which corresponds to an emission credit of about 8 kg (0.4/52.4) of CO_2. In other words, for a time horizon of 100 years, the storage of 1 tCO_2 for 1 year equates to an avoided emission of 8 $kgCO_2$. Emission delays for longer periods earn increasingly larger credits. Several subsequent impact assessment methods (Clift & Brandão, Dynamic LCA—see below) use further refinements of the Lashof method.

1.2.5 | Average carbon stocks approach

Kirschbaum et al. (2001) and Cowie, Kirschbaum, and Ward (2007) introduced the simple notion of using time-averaged carbon stocks as a method for carbon accounting. This method, seen as equally applicable for national- and project-scale accounting, is based on assessing the time-averaged carbon stocks under different land-use systems, and debits/credits are based simply on the difference between those averages under different land uses or land management systems. This method smooths out the temporal fluctuations in C stock in a managed forest. An increase/decrease in average C stocks is treated as a removal/emission that can be equated with avoided CO_2 emissions from fossil fuel displacement.

1.2.6 | Müller-Wenk and Brandão

The Müller-Wenk and Brandão method (Müller-Wenk & Brandão, 2010) is based on the Moura-Costa-1 method, but uses a 500-year time frame, over which the integral for a pulse emission of 1 tCO_2 is 183.6 tonne-years CO_2. To address the reversible nature of biogenic carbon emissions, it calculates a duration factor by taking the mean fraction in the atmosphere of 1 tCO_2 emission from fossil fuel combustion over 500 years. This is used as the basis for calculating the atmospheric lifetime of carbon released from biogenic sources, resulting in fossil-combustion-equivalents. It applies to all CO_2 fluxes from and to the biosphere and deals with temporary storage like the Moura-Costa-1 method, with the difference that the equivalence factor is –0.005 tCO_2 per CO_2 tonne-year of storage (1/183.6).

1.2.7 | Carbon balance indicator

The Carbon Balance Indicator method, described by Pingoud, Ekholm, and Helin (2016), is defined as the ratio of the difference in terrestrial C stocks and cumulative fossil fuel savings from bioenergy use. The method essentially compares the gain in cumulative savings in fossil fuel emissions against any carbon debt from reduced biospheric carbon stocks. If carbon stocks are increased over the assessment period, the change in carbon stocks becomes a benefit additional to substitution of fossil fuels. Thus, the results, as for other methods, depend on the timing and duration of the assessment period.

1.2.8 | Clift and Brandão

The Clift and Brandão (2008) method is based on the Lashof method and treats delayed GHG emissions by excluding radiative forcing outside the 100-year assessment period. Unlike the Lashof method, calculations are applied consistently to any biogenic and fossil fuel GHG flow, not only CO_2 sequestration, and can be used for both a single-pulse GHG release and for ongoing release over extended periods. These expressions have been incorporated into the BSI/Carbon Trust PAS 2050 specification for carbon footprint calculation (BSI, 2008) as an optional approach to quantify the effects of timing of GHG emissions. Brandão (2012) calculated a set of credits/factors for emissions relative to the time by which they are delayed.

1.2.9 | ILCD

The International Reference Life Cycle Data System (ILCD) handbook (European Commission, 2010) recommends that, in addition to the use of GWP_{100}, all biogenic carbon fluxes (both emissions and removals) should be accounted for by using a set of specified rules. In general, it recommends that the impact of temporary carbon storage and delayed emissions should be excluded unless their accounting is the specific focus of a project, in which case it recommends that all net fluxes, whether from biogenic or fossil origins, should be treated in the same way. For calculating credits for delayed emissions or temporary storage, it recommends the use of a 100-year time horizon and to simply subtract 1/100 of the emission for each year of storage or emission delay. Any delayed GHG emission is multiplied by its GWP_{100}, but that is reduced by the number of years of delay and its linear coefficient (1/100).

1.2.10 | Time correction factors and time-adjusted warming potentials (TAWP)

Kendall, Chang, and Sharpe (2009), Kendall (2012) proposed two approaches intended to retain the CO_2 equivalent unit common to LCA practice and GHG emission policies, while capturing the effects of timing of GHG fluxes. They devised two alternative scaling factors to modify GWP calculations: time correction factors and time-adjusted warming potentials (TAWP). Both approaches use relative cumulative radiative forcing as the basis of calculation and were developed with a focus on minimizing barriers to adoption for non-expert practitioners. The time correction factors were first proposed in the context of indirect land-use change (iLUC) emissions resulting from biofuel projects (Kendall et al., 2009). The factors illustrated and corrected the undervaluing of the impacts of iLUC emissions due to the practice of amortizing these emissions.

Kendall (2012) then presented a more complex version of the factors for emissions, credits and variable time frames in the context of life cycle-based vehicle emission regulations. Kendall and Yuan (2013) apply this approach to bioenergy systems. The TAWP calculates time corrected CO_2 equivalent emissions directly and has been made available as an open-source tool intended for use in LCA calculations (Kendall, 2012).

Here, we have illustrated only the TAWP—updated with the most recent reparameterization of the CO_2 decay curve (Joos et al., 2013). We did not cover time correction factors as they were developed for the narrow case of amortized emissions, while the TAWP can be applied to GHG fluxes occurring throughout a life cycle using any chosen analytical time horizon, and both methods share the same focus on cumulative radiative forcing.

1.2.11 | Dynamic LCA

The Dynamic LCA method of Levasseur, Lesage, Margni, Deschênes, and Samson (2010) is numerically identical to the earlier Clift and Brandão (2008) method, where emissions are characterized with respect to their timing. In the Dynamic LCA, any CO_2 fluxes are time explicit. The method quantifies and sums radiative forcing resulting from all life cycle emissions and removals attributable to an activity over any chosen time horizon. The main purpose of the development of the dynamic LCA method was to explicitly present radiative forcing over time so that LCA practitioners could see its temporal evolution and perform their own chosen analyses without being restricted to arbitrarily chosen time horizons. The method has been applied in an assessment of biofuels (Levasseur et al., 2010), an afforestation project (Levasseur, Lesage, Margni, Brandão, & Samson, 2012) and the LCA of a wood product in which the method was compared with other carbon accounting approaches (Levasseur, Lesage, Margni, & Samson, 2013).

1.2.12 | GWPbio

Cherubini, Peters, Berntsen, Stromman, and Hertwich (2011) developed characterization factors specific for CO_2 emissions from biomass combustion in order to account for the impact of temporary biogenic carbon release before re-sequestration during plant regrowth. With the GWP_{bio} method, the processes removing CO_2 from the atmosphere are modelled through the use of convolution integrals, resulting in impulse response functions (IRFs) for bioenergy CO_2 emissions that are similar to those used for other GHGs. Emission metrics like the commonly known GWP, GTP, etc., can thus be consistently computed and used to directly convert emission flows to CO_2-equivalents (Cherubini, Bright, & Stromman, 2012). In this approach, the carbon sink from forest regrowth is integrated with other C cycle components to model the climate system response to an emission. This means that the CO_2 sequestration by plant regrowth must not be reported as an inventory item to prevent double counting, as it is included in the associated characterization factor. This approach has been used in various LCA applications of bioenergy and biomass systems (Bruckner et al., 2014; Cherubini, Bright, et al., 2012; Cherubini, Stromman, & Hertwich, 2011; Guest, Cherubini, & Stromman, 2013a, 2013b). Simple equations are made available to compute these characterization factors on the basis of biomass rotation periods and forest residue removal rates Cherubini, Huijbregts, et al. (2016).

1.2.13 | O'Hare

O'Hare et al. (2009) introduced the notion of explicitly including time preference into climate change impact assessments that have variable time profiles. Discounting is an explicit way of dealing with time by giving greater weight to near-term costs and benefits and assigning continuously decreasing weight to more distant ones. This explicit discounting of impacts contrasts with all other methods applied here, although the other methods also implicitly include a simple type of "discounting" of emissions by excluding any impacts beyond the end of a certain time horizon.

The use of economic concepts (like discounting for time preference) is uncommon in environmental assessments like carbon footprinting. Their use is controversial as discussed in a number of papers (Nordhaus, 2007; O'Hare et al., 2009; Stern, 2007; Sterner & Persson, 2008), including a special IPCC report on accounting methods (Plattner et al., 2009). To date, no consensus has been reached on the appropriateness of including discounting in environmental assessments. While O'Hare et al. (2009) introduced a methodology for time discounting, they, too, did not suggest appropriate discount values to use. The O'Hare Method calculates radiative forcing resulting from the net effect of GHG emissions and removals in every year. In the present work, we then applied (traditional exponential) discount rates of 0%, 1% and 5% to calculate discounted results over a 100-year assessment period.

1.2.14 | Climate change impact potentials (CCIPs)

Kirschbaum (2003, Kirschbaum, 2014) described three different kinds of climate change impacts: impacts related directly to future temperatures (e.g., heat wave impacts), impacts related to the rate of warming (e.g., for ecological or societal adaptation) and impacts related to cumulative warming (e.g., sea-level rise). It is generally accepted that all three kinds of impacts are important (Fuglestvedt et al., 2003; Tanaka, Peters, & Fuglestvedt, 2010), and Kirschbaum (2014) developed an approach by which they can be calculated and combined into a single index, termed Climate Change Impact Potential (CCIP).

In essence, this approach first involves calculating the temperature, rate of warming and cumulative warming for each year over a defined assessment horizon, such as 100 years, and under a chosen background emission scenario, such as RCP 6.0. Any bioenergy project then leads to changes in the climatic factors underlying the three different kinds of impacts, leading to newly assessed impacts. These additional impacts are summed over the assessment horizon to give marginal net impacts due to any activity.

Marginal climate change impacts can then be compared between different activities like pulse emissions of different GHGs (Kirschbaum, 2014) or bioenergy use (Kirschbaum, 2017). The approach allows comparison of marginal climate change impacts resulting from different activities, such as using bioenergy or generating the same amount of end-use energy from burning fossil fuels (Kirschbaum, 2017).

1.2.15 | Climate tipping potential (CTP)

The Climate Tipping Potential (CTP) is based on the notion that there are thresholds or tipping points in the global climate system (Lenton et al., 2008) that need to be avoided to prevent detrimental climatic changes (Jørgensen, Hauschild, & Nielsen, 2014, 2015). A threshold can also be a politically set maximum climatic change level. The climate change threshold is quantified as a maximum temperature increase, for example, 2°C, expressed as a corresponding atmospheric CO_2 concentration. The method then calculates the capacity of the atmosphere to absorb GHG emissions without exceeding the tipping point, and any emission is assessed against that remaining capacity. When the global temperature is still significantly below a threshold temperature, any extra emissions uses a relatively small fraction of the atmosphere's remaining capacity to remain below the threshold level. As one gets closer to the threshold, the remaining capacity of the atmosphere diminishes and correspondingly greater weight is given to additional emission units. As the CTP method is meant for assessing impacts related to staying below a specific target, emissions/removals occurring after passing of that threshold are not included. This is a direct consequence of the target focus, which is absent from other methods, and the CTP method should be used only to assess the impact related to staying below a threshold. Thus, the CTP method is intended to be used in conjunction with methods for assessing long-term climate change impacts, such as GWP, with a sufficiently long assessment period, in order to transparently include a focus on both the target and long-term impacts.

In this study, we assumed a temperature increase threshold of 2°C above preindustrial levels. As the CTP metric addresses radiative forcing levels, this temperature threshold is expressed in terms of an atmospheric GHG concentration of 450 ppm CO_2-eq. (Jørgensen, Hauschild, & Nielsen, 2014), with the argument that below this atmospheric GHG concentration level, there is at least a 50% chance of stabilizing the climate at the 2°C temperature increase (Hare & Meinshausen, 2005; Marchal et al., 2012; Schneider et al., 2007).

2 | MATERIALS AND METHODS: APPLICATION OF IMPACT ASSESSMENT METHODS TO BIOENERGY CASE STUDIES

This section demonstrates the application of the 15 impact assessment methods to three simplified hypothetical bioenergy systems that differ in their temporal profile of CO_2 emissions and removals. We apply the impact assessment methods to estimate the climate change mitigation potential of each case study. For simplicity and transparency, we include only CO_2 emissions and removals, to elucidate differences in the results that are caused by differences between the various methods. Specifically, we analyse the following:

1. a forest grown for bioenergy over a 25-year rotation, replacing a carbon-rich mature forest;
2. a forest grown for bioenergy as in Case Study 1, but established on pasture land; and
3. an annual energy crop, grown on previous cropland.

The reference scenarios (baselines) use the three respective systems with stable carbon stocks (mature forest, pasture or cropland) producing no bioenergy. They represent different profiles in terms of initial biospheric carbon stocks and cumulative biomass produced, as well as the timing of carbon flows. The case studies are chosen to highlight the

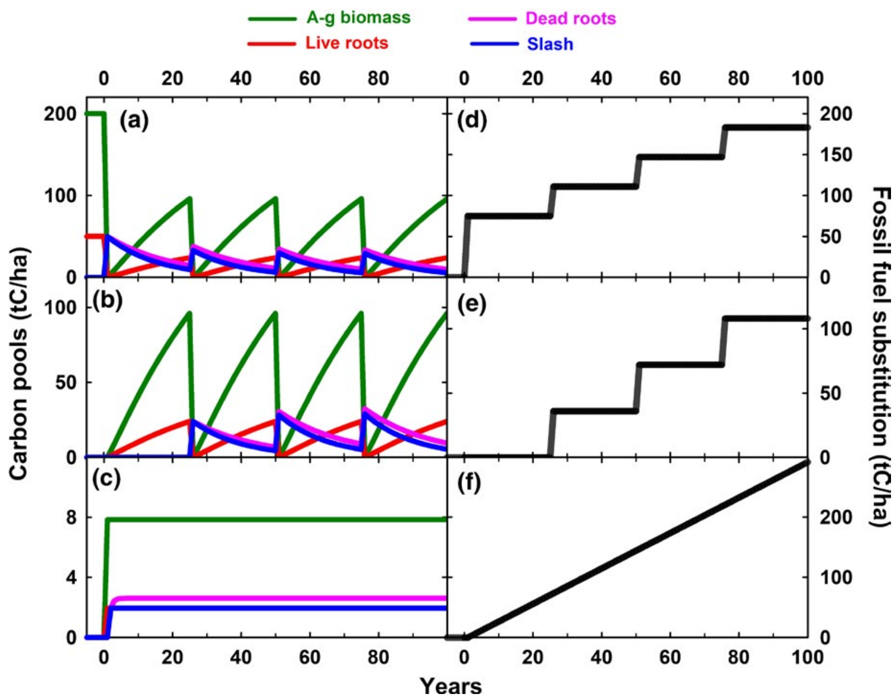

FIGURE 1 Changes in biospheric carbon pools over time for the three bioenergy case studies (a–c) and the corresponding cumulative fossil fuel use substitution benefit from the use of bioenergy (d–e). Note that different scales are used for the different case studies and for forest C stocks and saved fossil fuel emissions in the different panels. Panels a and d refer to Case Study 1, panels b and e to Case Study 2 and panels c and f to Case Study 3

differences between the impact assessment methods and are not intended to represent any specific actual systems. Thus, results from this study should only be used for making comparison between the different assessment methods, but are not intended to infer the climate change effects of actual bioenergy systems.

Case Study 1 starts with a carbon-rich forest containing 200 tC/ha in above-ground biomass (Figure 1a), while Case Studies 2 and 3 include no initial biomass. The harvested biomass is assumed to substitute for fossil fuels with 50% efficiency. That means that 1 tC from harvested biomass can generate the same amount of end-use energy as 0.5 tC fossil fuels. This factor has also been called "displacement factor" (Schlamadinger & Marland, 1996) and is a key factor determining the overall benefit of using bioenergy. Substitution efficiencies vary widely depending on energy and carbon contents of different bioenergy products and fossil fuels and their conversion efficiencies to useable end-use energy (Davis, Anderson-Teixeira, & DeLucia, 2009; Ioelovich, 2015). The 50% substitution efficiency also incorporates emissions associated with bioenergy supply chains, such as from fertilizer, harvesting and transport of biomass, and correspondingly for fossil fuels, from mining and transport. In addition, we assume that 25% of above-ground biomass (representing leaves, small branches, stumps, etc.) remains unutilized in the forest as slash.

A simple growth model is used to quantify above- and below-ground live biomass (Kirschbaum, 2017). At harvest, living roots became dead roots. Dead roots and slash remain in the forest and decompose exponentially over time, thereby releasing their stored carbon (Repo, Tuomi, & Liski, 2011). We assume that soil carbon remained constant in each case.

Table 1 shows the values of the parameters adopted for the case studies.

In the reference scenarios, it is assumed that fossil fuels are used to generate the same amount of end-use energy as could be generated from the bioenergy options. For the bioenergy production system, the changes in biospheric carbon stocks are included in the calculation of net CO_2 emissions in accordance with the requirements of the different impact assessment methods. The difference in CO_2 fluxes between the bioenergy and fossil fuel systems are then used to calculate marginal changes in atmospheric CO_2 concentration, radiative forcing and temperature over time. This provides the relevant input information for the different impact assessment methods. Additional details of the case studies and specific calculations for each of the impact assessment methods are given in the Supporting information (Appendix S1).

We do not include effects of other greenhouse gases, albedo or other biogeophysical effects that affect climate forcing, nor do we include indirect land-use change. These factors can strongly influence the results of an assessment of climate change impacts of bioenergy systems (Cherubini, Bright, et al., 2012) and should be included in studies that aim to comprehensively quantify the climate change effects of bioenergy. They are not included here because of the exclusive focus of the present work on a comparison between different assessment methods.

The different impact assessment methods use different functional forms and express their findings in different units. Hence, in order to standardize the comparison of

TABLE 1 Parameters used for the case studies

	25-year rotation replacing mature forest	25-year rotation replacing pasture	Crop replacing crop
Management parameters			
Rotation length (years)	25	25	1
Initial age (years)[a]	1,000[a]	0	0
Initial biomass above- and below-ground (tC/ha)	250	0	0
Gaps between rotations (year)[b]	1[b]	1	0
Ecophysiological parameters and properties of the production system			
Biomass retained as slash (% of above-ground biomass)	25	25	25
Biomass used for bioenergy (% of above-ground biomass)	75	75	75
Substitution efficiency (%)	50	50	50
Root:shoot ratio	0.25	0.25	0.25
Root decay (% per year)	5	5	75
Slash decay (% per year)	6.67	6.67	100
Parameters of the growth equation			
B_{max} (tC/ha)	250	250	250
k_1 (per year)	0.03	0.03	0.04
k_2	1.1	1.1	1
Emergent property			
Above-ground biomass at harvest time (tC/ha)[c]	96	96	8

Details of all calculation are given in Supporting information (Appendix S1).
[a]This notional age simply means that the stand has reached maximum carbon stocks. [b]Assumes that there is a gap year between rotations, hence a year without carbon increment. [c]With the parameters and rotation lengths used, the stated above-ground biomass results.

impact assessment methods, we use two key indices for each method. These indices are the Carbon Neutrality Factors, CN_e (Schlamadinger, Spitzer, Kohlmaier, & Lüdeke, 1995; Zanchi et al., 2012), and the Bioenergy Mitigation Potential, *BMP*. The CN_e compares bioenergy and fossil fuels use, in each case normalized to the same amount of end-use energy, and defined as:

$$CN_e = 1 - C_b / C_f \quad (1)$$

where C_b is a measure of the climate effect related to the CO_2 emissions per unit of land used for bioenergy production, and C_f is the climate effect of the corresponding CO_2 release through fossil fuel use. Both measures are quantified for the generation of the same amount of end-use energy. Among the different impact assessment methods, the assessed measure of the climate effect could be changes in carbon stocks, radiative forcing, temperature, a measure of ultimate climatic impacts (as the ultimate impact end points) or an index related to the proximity to specific tipping points in the climate system. In all cases, we followed the rules and equations that are presented in the publications that describe each method. All case studies span 100 years.

If the resultant values of CN_e are negative, it indicated that bioenergy use would result in worse climate outcomes than the use of fossil energy (within the limitations of the study). Positive values between 0 and 1 indicate that the use of bioenergy leads to better climate outcomes than the use of fossil fuels, but still resulted in adverse biospheric carbon stock changes compared with the reference case. Positive values greater than 1 indicate that bioenergy use not only has better climate outcomes than the use of fossil fuel, but leads to C sequestration benefits in addition to the generation of end-use energy without burning fossil fuels.

Negative values can arise from the conversion of a carbon-rich forest to a bioenergy plantation if cumulative fossil fuel substitution benefits are insufficient to compensate for the loss of forest carbon stocks. The value can be around 1 for the use of agricultural crops on former agricultural land, where only minor changes in biosphere carbon stocks are involved; values can be greater than 1 where forests are planted on former cropland, and where increasing on-site carbon stocks add to the overall benefit.

We also use a second index, the Bioenergy Mitigation Potential, BMP, which compares the fossil energy displacement benefit of bioenergy production per unit land area with the effect of saving one unit of fossil fuels at the beginning of the assessment period. Hence, BMP is defined as:

$$\mathrm{BMP} = C_{ff(1)}/C_f \quad (2)$$

where $C_{ff(1)}$ is the calculated effect arising from the emission of 1 tC of fossil fuels emitted in year one of the calculation period, and C_f has been defined above. This index provides a measure of the mitigation value of using 1 ha of land for bioenergy production for 100 years, compared with the effect of saving the emission of 1 tC of fossil fuels in year 1.

3 | RESULTS

Figure 1a–c show biospheric carbon stock changes under the three bioenergy case studies, and Figure 1d–f show the corresponding CO_2 savings due to fossil fuel substitution. At harvest times, all trees or bioenergy crops are cut, with 75% of above-ground biomass harvested and removed while 25% remained on site as slash, and live roots became dead roots. Dead tree roots and retained slash on the forest floor then decay slowly over time. The key features of the three systems are that Case Study 1 is characterized by an initial loss of biospheric carbon that is gradually offset through forest regrowth and accumulating fossil fuel substitution at each harvest. In Case Study 2, increases in biospheric carbon stocks add to the benefit of fossil fuel substitution, and in Case Study 3, biospheric carbon stocks remain at an unchanged low level so that neither gains nor losses play an important role.

Specifically, in Case Study 1 (Figure 1a), there is a large initial carbon loss when the mature forest is harvested. Thereafter, the forest is regrown and repeatedly harvested at 25-year intervals, leading to accumulating fossil fuel substitution benefits (Figure 1d). The pattern is similar for Case Study 2, apart from the absence of the initial harvest and its associated carbon losses (Figure 1b, e). In Case Study 2, there are thus three harvests over the 100-year simulation period, whereas there are four harvests in Case Study 1, with the next harvest scheduled just beyond the assessment horizon. Case Study 3 has only minor changes in stand biomass (Figure 1c) but a steadily increasing amount of fossil fuel substitution due to annual biomass harvests (Figure 1f).

The 15 impact assessment methods are applied to each of the three bioenergy case studies. Figure 2 shows the comparison for all three case studies. Results are expressed as Carbon Neutrality Factors for each method applied here (see Methods in Section 2.1). Details of the calculations of each impact assessment method are given in the Supporting information (Appendix S1).

3.1 | Forest after forest

The strongest contrast between impact assessment methods is seen in Case Study 1, where the different impact assessment methods generate a wide range of Carbon Neutrality Factors, ranging from about –0.6 under the O'Hare (5%) and –0.5 under the Moura-Costa-2 method to about 0.67 under the Lashof, and 0.74 under the Müller-Wenk and Brandão method, with some other methods giving values of about 0.4 to 0.5. Other methods give values that are spread somewhere between these extremes. It is interesting that nearly the widest divergence is calculated between the two interpretations of the same method (Moura-Costa).

This comparison shows the wide range of apparent potential climate change mitigation benefits that can be estimated by simply focusing on different aspects of climate change. Those aspects range from a simple balance of carbon flows to effects to radiative forcing and temperature, either in instantaneous or integrated form, with varying treatments of time. The selected methods also embed different value-based choices or conceptual interpretations to the same underlying bioenergy scenario. Approaches developed in the 1990s to credit carbon storage in products were based on simplified constructs, while more recent methods encapsulated a more realistic representation of the physical climate system. Application of the former to bioenergy systems is risky, because they were not specifically developed to assess bioenergy CO_2 emissions, unlike some of the newer methods.

For the calculations shown here, all methods use the same information about the bioenergy system being modelled, with the same carbon flows (emissions and removals) available to all methods. The difference between methods lay solely in how this information is used and interpreted. In understanding these differences, it is important to keep in mind that Case Study 1 is characterized by a large initial carbon loss (Figure 1a) that is eventually counterbalanced by accruing benefits from fossil fuel substitution (Figure 1d). The extent of that counterbalancing depends on the calculation procedure used by each method.

The largest positive Carbon Neutrality Factors is calculated with the Lashof method (0.67), whereby the assessed bioenergy benefit is calculated on delayed carbon fluxes from forest regrowth, as earlier carbon flows count more than later ones. The value is relatively large because the total carbon stored in all carbon pools on the regrown plantations following forest

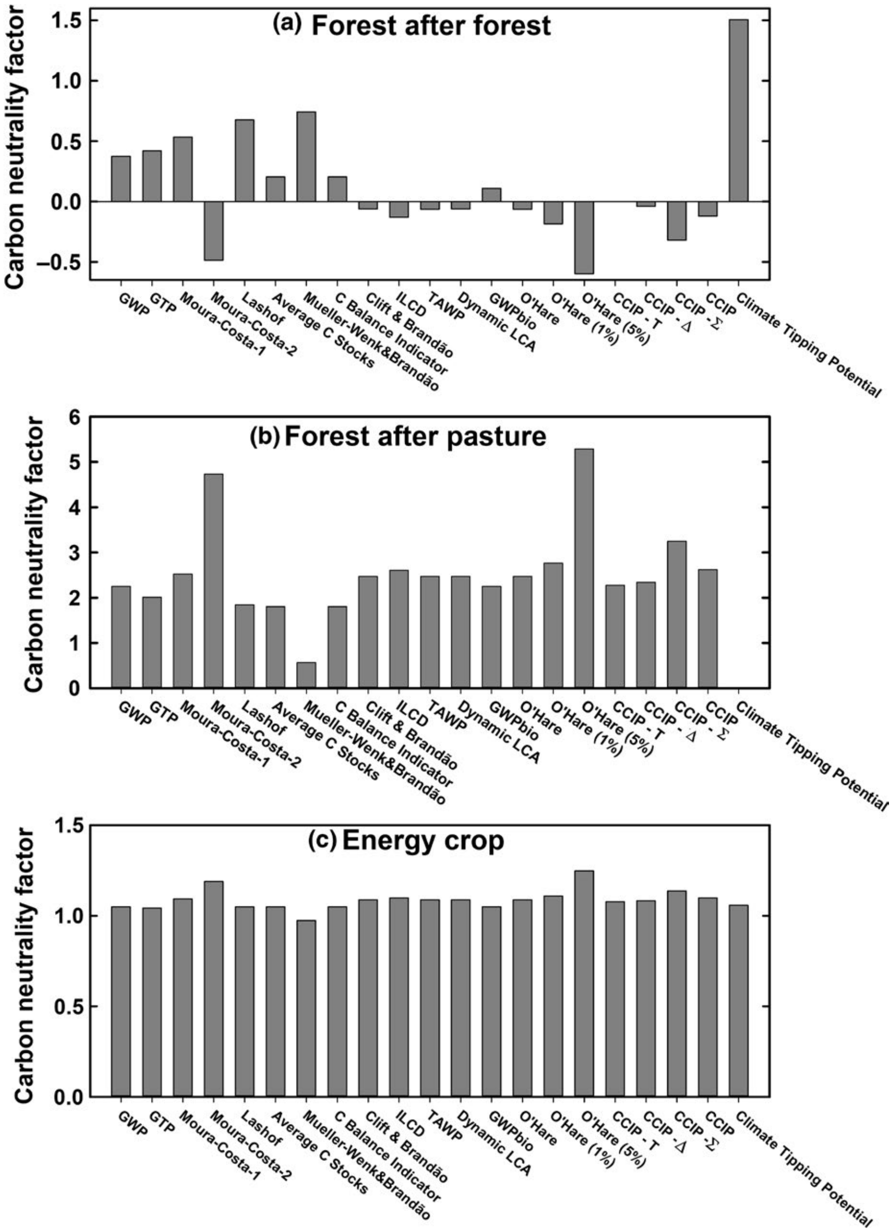

FIGURE 2 Carbon Neutrality Factors calculated with different impact assessment methods for the three case studies (a) bioenergy forest replacing carbon-rich forest; (b) bioenergy forest replacing pasture; and (c) annual energy crop on previous cropland. Higher numbers correspond to more beneficial assessments of the bioenergy option. Numbers greater than 0 mean that the bioenergy scenario is better than the use of fossil fuels. A value of 1 implies that the bioenergy scenario is completely carbon neutral, with neither positive nor negative additional carbon stock implications. Numbers greater than "1" imply that the bioenergy scenario has direct carbon storage benefits in addition to fossil fuel substitution benefits. For the O'Hare method, calculations are shown with discounting of 0%, 1% and 5% to calculate net present values. For Climate Change Impact Potentials, values are given for the integrated measure and separately for the three constituent impacts, direct warming (CCIP-T), rate-of-warming (CCIP-Δ) and cumulative warming impacts (CCIP-∑)

conversion amount to average carbon stocks of about 85 tC/ha, or around 8,500 tC-year/ha over 100 years, which, together with the fossil fuel substitution, largely counterbalance the initial carbon loss through harvest of the original forest.

A high value is also calculated with the Global Temperature change Potential (GTP). In this case, it is attributable to the specific interaction between the timing of carbon emissions, feedbacks via the carbon cycle and the GTP's exclusive focus on temperature changes at the end of the assessment period. In Case Study 1, carbon is released at the initial harvest at the start of the 100-year assessment period. That allows much of the carbon to be absorbed by the oceans so that only half of it still resides in the atmosphere at the end of the 100-year assessment period when its effect on temperature is calculated. In contrast, savings from fossil fuel substitution accumulate from the bioenergy from the four harvests over the 100-year period, leaving less time for carbon cycle feedbacks to reduce that beneficial effect. The actual temperature is therefore significantly reduced at the end of the assessment period. While this reduction is accompanied by temporary temperature increases at intermediate times within the assessment period, those increases make no impact contribution as the method focuses exclusively on the endpoint temperature.

The largest negative Carbon Neutrality Factors is calculated with the O'Hare method using a 5% discount rate. In this case, the large negative value is due to the full counting of the large initial carbon loss combined with substantial discounting of the subsequent gains through fossil fuel substitution. With a 5% discount rate, neither fossil fuel substitution nor biospheric carbon stock changes beyond the first rotation significantly contribute to these calculations.

We also calculate a large negative value (–0.5) for the Moura-Costa-2 method. It is unexpected how different this calculated value is compared with the Moura-Costa-1 method (see above), which reflects fundamentally different interpretations of essentially the same method. In the Moura-Costa-2 method, emissions from fossil fuels and the biosphere are treated consistently, whereas in the Moura-Costa-1 method, credits are given only to additional carbon sequestration. The large negative value results because the method accounts fully for the large initial carbon loss incurred during the initial harvest, but it only accounts for half the fossil fuel benefit realized over the full 100 years, as flows are weighted as 0 after 53 years (Brandão et al., 2013; Supporting information Appendix S1), essentially excluding the large fossil fuel substitution benefit over the second half of the 100-year period.

Relatively large negative values are also calculated for cumulative warming impacts as part of the Climate Change Impact Potential calculations (CCIP-$\sum$). Cumulative warming is a relevant measure for impacts such as sea-level rise. This calculation essentially retains a memory of any warming or cooling over any part of the assessment period. In Case Study 1, the initial emission of forest carbon leads to an increase in atmospheric CO_2 concentration and consequent warming. Fossil fuel substitution benefits eventually lead to a reduction in atmospheric CO_2 concentration and cooling at that time. However, that cooling is insufficient to completely negate the warming during the earlier period so that cumulative warming impacts are still larger than those from fossil fuel-based energy production.

For the other two impact types that together constituted the Climate Change Impact Potential—direct warming impacts and rate-of-warming impacts—calculated impacts over the 100 years are very close to 0 so that the average of the three impact types is only slightly negative. This contrasts with the calculations based on Global Warming Potentials, Average Carbon Stocks, and Carbon Balance Indicator impact assessment methods, which ignore the timing of emissions on radiative forcing leading to fairly large positive numbers.

3.2 | Forest after pasture

Figure 2b shows the results of the impact assessment methods for Case Study 2. This case study differs from Case Study 1 in that it starts with low biospheric carbon stocks so that the growth of a bioenergy plantation generates benefits through increasing biospheric carbon stocks (Figure 1b) in addition to fossil fuel substitution (Figure 1e). Consequently, all impact assessment methods calculate Carbon Neutrality Factors greater than 1 (Figure 2b). The lower variance of calculated factors for Case Study 2 than for Case Study 1 means that conclusions drawn about the merits of bioenergy compared with the use of fossil fuel-based energy are less strongly affected by the choice of method for Case Study 2 than for Case Study 1. While for Case Study 1, the choice of impact assessment methods could result in bioenergy being judged to be anything between highly beneficial to detrimental, for Case Study 2, all impact assessment methods lead to beneficial assessments, although numerically Carbon Neutrality Factors still range substantially (Figure 2b).

The highest Carbon Neutrality Factors are calculated for the O'Hare method, with a 5% economic discount rate and the Moura-Costa-2 method. Calculated numbers are so large because the early increase in biospheric carbon stocks when a new forest is planted on agricultural land is valued very highly under both impact assessment methods, whereas the later fossil fuel substitution is of lesser importance so that the ratio of adjusted biospheric carbon gain to the fossil fuel substitution benefit is particularly high.

Lowest values are calculated under the Müller-Wenk and Brandão method. Under the Climate Tipping Potential method and the particular parameters used here, there is no fossil fuel substitution benefit calculated at all because the first harvest is scheduled after the time of reaching the defined climate tipping point. In general, Carbon Neutrality values calculated with Climate Tipping Potentials vary enormously with just slight changes in model assumptions or set threshold values because these values are extremely sensitive to the particular timing of the key events, such as harvest dates, together with emissions/removals at those times. The low result under the Müller-Wenk and Brandão method is due to biospheric carbon storage being accorded a very low credit: only just over 0.5% of actual biospheric carbon stocks is credited in each year of storage.

3.3 | Annual crop on arable land

Figure 2c shows Carbon Neutrality Factors of an annual energy crop planted on land previously used for agricultural crops. This case study therefore has only minor biospheric carbon stock implications, meaning that the benefit of fossil fuel substitution does not need to be compared against any losses or gains of biospheric carbon stocks. All calculated Carbon Neutrality Factors are therefore close to 1, with only minor differences between values calculated with different impact assessment methods (Figure 2c).

While the calculated Carbon Neutrality Factors reveal few differences between numbers calculated with the different impact assessment methods, more interesting differences emerge when the different impact assessment methods are used to calculate Bioenergy Mitigation Potentials (Figure 3). In this case, results of bioenergy use are compared against the saving of 1 tCO_2 from fossil fuels in year 1.

The simple, carbon-based impact assessment methods, such as the Average Carbon Stocks Approach or the C Balance Indicator, or integrated radiative forcing sums

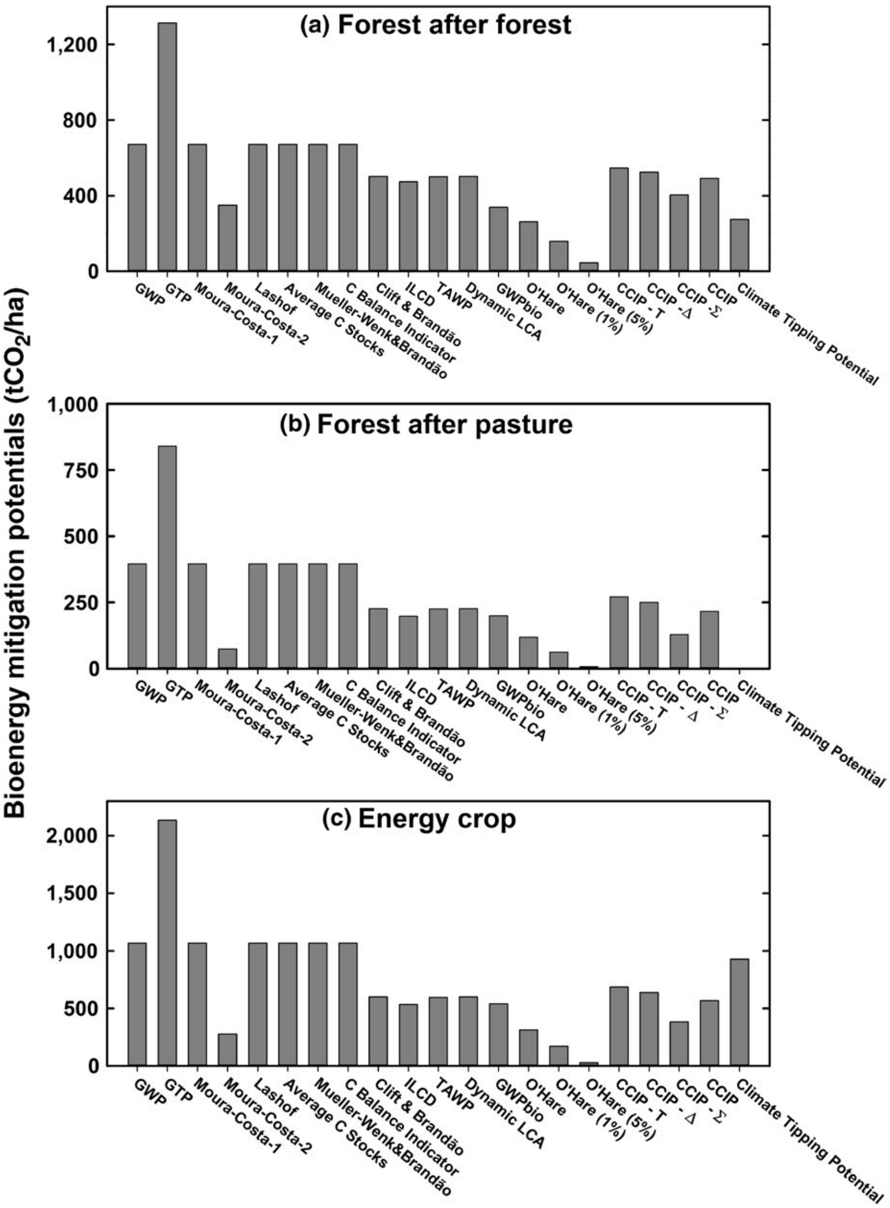

FIGURE 3 Bioenergy mitigation potentials expressed as the amount of biomass energy that can be generated from one hectare over 100 years relative to 1 tCO_2 emitted in year 1. A value of 1,000, for example, means that 1 ha used over 100 years according to the bioenergy scenario could mitigate climate change effects equivalent to the avoided emission of 1,000 t fossil CO_2 in year 1

without adjustments, using GWPs, all suggest similar fossil fuel mitigation potentials by the bioenergy scenario of about 1,000 tCO_2/ha (Figure 3c). The energy crop case study suggests an annual above-ground biomass production of about 8 tC ha^{-1} $year^{-1}$ (Figure 1c). The scenario assumes that 75% of biomass is usable for bioenergy that could substitute for fossil fuels with 50% efficiency to generate fossil fuel savings of about 3 tC ha^{-1} $year^{-1}$ or 300 tC/ha (equivalent to about 1,000 tCO_2/ha) over 100 years.

The mitigation potentials are somewhat lower for the forest-after-pasture case study (Figure 3b) because it is assumed that the agricultural crops have higher growth rates than forests. In the comparison between the two forest case studies, the forest-after-forest case study (Figure 3a) has a higher mitigation potential because the harvest of the original forest at the start of the project contributes to the overall mitigation potential.

There are interesting differences between the different assessment methods. The differences between the different discount rates used with the O'Hare method are quite stark and easy to understand. The O'Hare method is based on calculated avoided radiative forcing within the 100-year assessment period so that fossil fuel substitution later within the 100-year assessment period contributes less than earlier activities, like a fossil fuel saving in year 1 that is used as the basis of comparison. That explains that there is low calculated mitigation potential even without using any discount rates. When later savings are further discounted, especially at the high 5% discount rate, calculated mitigation potentials are very low because the fossil fuel emission in year 1 is assessed as highly important, whereas the ongoing fossil fuel displacement is increasingly discounted over time so that, overall, the agricultural crop is assessed to provide very little mitigation benefit.

In contrast, the highest mitigation potentials are calculated with the GTP under all case studies. The large mitigation potential of the GTP is due to its exclusive focus on the temperatures reached at the end of the 100-year assessment period. Responding to a one-off pulse emission of CO_2, in year 1, 100 years later, the atmospheric CO_2 concentration is changed by only about half the initial change, hence reducing the importance of early fossil fuel emissions for ultimate temperature changes. In contrast, the fossil fuel savings through bioenergy use that accrued towards the end of the 100-year assessment period left little time for these carbon cycle feedbacks to reduce the atmospheric CO_2 concentration and lead to a relatively large temperature reduction.

Interestingly, the direct temperature impact component of the Climate Change Impact Potential that is based on the same temperature calculations as the GTP results in a much smaller mitigation potential than the GTP. This is principally because the relevant impact is calculated as the sum of impacts in each of the 100 years of the assessment, instead of focusing solely on the endpoint temperatures at the end of the assessment horizon, which give it a much lower overall assessed mitigation potential.

Some methods calculate the radiative forcing from the time of emissions/removals to the end of the assessment period, and with later activities, much of the resultant radiative forcing occur beyond the end of the assessment horizon and is, therefore, not counted. This is the case for Moura-Costa-2, Lashof, Clift and Brandão, O'Hare, Dynamic LCA, Time-Adjusted Warming Potentials and ILCD.

4 | DISCUSSION

The application of 15 impact assessment methods for climate change to three case studies shows that the relative climate change mitigation potential of using bioenergy in lieu of fossil fuel generated energy is highly variable and dependent on the choice of method for the forest to forest case, whereas results are more consistent in the other two case studies. The difference between methods is mainly due to the different approaches, which include both simple schemes initially developed for crediting carbon storage in products and more recent sophisticated approaches with better modelling of the underlying physical mechanisms (Breton et al., 2018). The different methods also address different research questions and are derived for different contexts. Each method has a specific meaning, interpretation, applicability domain and limitations, with which researchers should be familiar, before applying them in any study. When policymakers aim to broadly assess the climate change impact mitigation potential of using bioenergy, they need to ascertain whether specific methods have been developed to answer that question or for other, specifically defined applications.

Our analysis shows that detailed accounting for the timing of emissions is important, especially for bioenergy systems that involved large gains and losses of carbon at different times within the assessment period. This is particularly clear in Case Study 1, in which the bioenergy system replaces forested land. This is precisely the circumstance where a sophisticated analysis is necessary to appropriately assess the benefit of fossil fuel substitution against the large initial carbon emission related to the land-use change incurred by the bioenergy system.

All methods essentially aim to estimate impacts by using simplified approaches that vary between the methods. Methods differ in several aspects, such as the point along the cause-effect chain at which a mid-point or endpoint indicator is selected (e.g., radiative forcing, temperature change or others) and in their conceptual interpretation of time considerations (Breton et al., 2018; Levasseur et al., 2016; Zanchi et al., 2012). Different methods are available to capture the different aspects of climate change that should be considered. For example, climate change impacts can be related to three different aspects: (a) long-term temperature increases, (b) the rate of warming and (c) cumulative warming (Fuglestvedt et al., 2003; Kirschbaum, 2014; Tanaka et al., 2010). Focus on one or the other of these three temperature-related variables leads to different assessed net impacts of using bioenergy (cf. CCIP-T, CCIP-Δ and CCIP-Σ in Figures 2 and 3), but at present, there is not yet adequate scientific understanding of the relative importance of these different climate impacts. Such scientific understanding needs to be combined with a consideration and acknowledgement of different perspectives across the global community, related to different peoples' circumstances and world views to guide appropriate policy choices on the adoption of future mitigation policies.

Increasing the capacity of users to make an appropriate choice of methods requires them to be informed about the meaning of the different methods. In turn, this requires that the scientific community openly discuss the different methods, progress towards agreed methodology for different applications and develop guidance on choosing and using methods for assessing the climate change impact of products or activities. Development of agreed methodology and guidance on choosing methods would improve consistency in the assessment of the potential of bioenergy systems to mitigate climate change and prevent extrapolation of results out of context. It is, of course, important that agreed methods are consistent with the ultimate goals of climate change mitigation. Furthermore, the sensitivity of results shown here is likely to also pertain to the assessment of systems other than bioenergy that involve time-varying GHG removals and emissions. Guidance on appropriate assessment methodologies will therefore have broad application.

Despite the dominance of GWPs in LCA studies and carbon footprinting, the application of a wide range of different impact assessment methods between different studies has resulted in ambiguous outcomes and uncertainties, for example, in terms of the climate change mitigation potential of bioenergy systems relative to their fossil fuel counterparts, as demonstrated above. In recent years, however, some progress has been made towards agreed methodology and consistent assessment of climate change impacts, with the work carried out by the IPCC (Plattner et al., 2009), the European Commission (2010) and the UNEP/SETAC Life Cycle Initiative (Frischknecht & Jolliet, 2016; Frischknecht *et al*., 2016; Levasseur et al., 2016) and reviews of proposed approaches (Breton et al., 2018; Helin et al., 2013; Røyne et al., 2016).

Jolliet et al. (2018) recommended that users apply two climate change impact assessment methods that focus on different types of climate response and different time horizons, to assess two complementary dimensions of climate change: short-term impacts, notably relevant for the rate at which climate is changing (using GWP_{100}) and long-term impacts targeting temperature stabilization (using GTP_{100}) (Levasseur, 2017; Levasseur et al., 2016). This recommendation to use multiple methods that reflect either short-term or long-term impacts could be a useful starting point for enhancing comparability of future climate impact assessment studies of bioenergy systems.

The inconsistent application of methods that all purport to assess climate impacts, especially when methods are decided upon arbitrarily, could hamper the achievement of climate change mitigation goals. There is an urgent need for methodological guidance from the scientific community on identification of appropriate methods, so that systems capable of delivering real mitigation outcomes can be selected and promoted by policymakers and the general community. The intention of this review, comparison and discussion of impact assessment methods is to increase understanding of the methods amongst researchers and contribute to a constructive debate on the alternative methods available for the assessment of bioenergy systems.

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SUPPORTING INFORMATION

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