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Quantifying the climate effects of bioenergy – Choice of reference system

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ABSTRACT

In order to understand the climate effects of a bioenergy system, a comparison between the bioenergy system and a reference system is required. The reference system describes the situation that occurs in the absence of the bioenergy system with respect to the use of land, energy, and materials. The importance of reference systems is discussed in the literature but guidance on choosing suitable reference systems for assessing climate effects of bioenergy is limited. The reference system should align with the purpose of the study. Transparency of reference system assumptions is essential for proper interpretation of bioenergy assessments. This paper presents guidance for selecting suitable reference systems. Particular attention is given to choosing the land reference. If the goal is to study the climate effects of bioenergy as a part of total anthropogenic activity the reference system should illustrate what is expected in the absence of human activities. In such a case the suitable land reference is natural regeneration, and energy or material reference systems are not relevant. If the goal is to assess the effect of a change in bioenergy use, the reference system should incorporate human activities. In this case suitable reference systems describe the most likely alternative uses of the land, energy and materials in the absence of the change in bioenergy use. The definition of the reference system is furthermore subject to the temporal scope of the study. In practice, selecting and characterizing reference systems will involve various choices and uncertainties which should be considered carefully. It can be instructive to consider how alternative reference systems influence the results and conclusions drawn from bioenergy assessments.

1. Introduction

Bioenergy is expected to contribute to climate-change mitigation by providing energy services that displace fossil fuels while generating fewer greenhouse gas (GHG) emissions than the displaced fuels [1]. Assessing bioenergy effects on climate requires comparison of scenarios with and without bioenergy to determine the net difference in emissions and other climate-forcing factors [2, Chapter 11, p.88]. The reference system comprises the “without bioenergy” scenario. The use of land, energy, and materials in the reference system are important for determining net effects of bioenergy on climate.

Reference systems are often poorly or inconsistently defined, or not specified [3–5]. In the literature, a reference system may have different names: baseline; business-as-usual; counterfactual; reference case, scenario or situation; or shadow scenario [4,6–8]. The variable use of terminology can be confusing. The reference system is analogous to the baseline scenario used in multi-functional scenario analysis as the reference for modelling changes under various economic, environmental and social constraints [9,10], or the baseline applied in carbon offset projects to quantify the credits earned by the project [11]. A baseline scenario is common in economic analyses but may represent one of several hypothetical simulations where none is meant to represent the most likely description of land, energy and material use in the absence of bioenergy. The baseline scenario should not be confused with the *base year* applied in some environmental accounting and reporting schemes, such as the UNFCCC and the Kyoto Protocol: the base year is

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a historical benchmark against which emissions and removals during a specific timeframe are compared.

In this paper, the term 'reference system' is used to refer to a dynamic baseline scenario that excludes the studied 'bioenergy system.' 'Land reference' and 'energy reference' are discussed separately. 'Dynamic' is used to emphasize that during a specified time period, aspects of the reference which affect climate forcing, such as vegetation and carbon stocks, and energy source, are likely to change. The term 'relative climate effect' is used in this paper to describe the net climate forcing attributed to the bioenergy system when compared to the reference system. Assessment of net climate effects requires consideration of the climate effects associated with all resources used, including land, energy and material inputs.

Climate effects of bioenergy result from feedstock production, transportation, processing and use of bioenergy [2,12]. In addition, indirect climate effects can occur if the bioenergy system causes a change in other activities, for example, through influence on land, or energy and food markets [13–15]. Climate effects have generally been quantified as net effects of GHG emissions and removals, but recent studies [16] have shown that non-GHG climate forcers can significantly influence the climate impacts of a bioenergy system, for example when changes in land management alter reflectance (albedo) and particulate emissions. Thus, total net climate effects are a product of interactions among all climate forcers that differ when the bioenergy system is compared to a reference system. Climate forcers include greenhouse gas (GHG) emissions, albedo, latent heat, aerosols, black carbon and other particulates across the life cycle stages. The choice of which climate forcers are considered and how they are determined is critical [16–19]. The assumptions that define the reference system are important for all climate forcers.

Life Cycle Assessment (LCA) is a common method for quantifying the environmental impacts of a product system (product, process or service) or decision [20,21] serving the function of interest (e.g., energy services). The results of LCA studies are expressed on a functional-unit basis (e.g., impact per MJ of delivered energy). The intended application and the reasons for carrying out an LCA study determine the goal and scope of an LCA, as well as the functional unit, system boundary and other methodological choices. LCA standards [20,21] provide guidance on these aspects, but do not explicitly consider the choice of reference systems. ISO 13065 [17] provides two options for the reference system against which to compare bioenergy: business as usual (BAU) and "projected future" which modifies BAU to reflect expected changes in baseline trends over time (e.g., population, technology, consumption, etc.).

The importance of applying an appropriate reference system for evaluating the climate effects of bioenergy is widely recognized [1,4,7,22–30] as is the need to describe and justify the chosen reference system [8,17]. Nevertheless, carbon dynamics in the land reference are typically ignored in bioenergy studies [3,24,31], and some studies explicitly focus on the climate effects of biogenic carbon fluxes in a bioenergy system while excluding consideration of the reference systems [32–34]. However, carbon stocks in biomass and soil are explicitly included in several studies of forest bioenergy [35–44].

The lack of consensus on the appropriate land reference systems has contributed to misunderstanding and disagreements about the climate effects of bioenergy [3,45–55]. Different methodological choices can result in totally different conclusions, which may confuse the audience of bioenergy studies, including decision-makers. Consequently, recent publications emphasize the importance of coherent reference system selection, and that corresponding assumptions need to be justified and communicated [3,8,17].

The objective of this paper is to enhance understanding of the significance of the choice of reference system, and to provide guidance on the appropriate choice of reference system for quantifying climate effects of bioenergy in various contexts. This paper therefore provides a framework for choosing a suitable reference system for different research questions and discusses the benefits and challenges of each approach. The main focus of this paper is the choice of the land reference. While this paper concentrates on climate effects, the approach is relevant to the evaluation of broader impacts of bioenergy systems (e.g. biodiversity) and to analysis of other land-based production systems. This paper is the first of a series of papers on quantifying the climate effects of bioenergy developed by IEA Bioenergy Task 38 research network.

2. Goal and scope

The reference system should be chosen so that the comparison between the bioenergy system and the reference system responds to the question studied. Otherwise, the results and conclusions of the study may be misleading. The question itself depends on the goal of the study. Bioenergy may be derived from land dedicated to bioenergy feedstock cultivation, or from biomass that is a by-product of other land use(s) such as forestry and agriculture, or from processing or post-consumer residues and waste streams. However, the selection of the reference system depends on the goal of the study, rather than on the type of feedstock.

The goal and scope of bioenergy studies vary. For example, the goal may be to analyse the historical effects of a specific bioenergy chain or policy (retrospective analysis) or the potential effects of a proposed policy or a planned change in a biomass production system (future, prospective analysis). The scope of a study may range from options to manage a specified plot of land over a short time period, to national contexts over long periods [28,56]. Uncertainties of the bioenergy and reference systems increase as spatial and temporal scales increase, in particular for prospective analyses [53].

LCA approaches have been classified as *attributional LCA* [57,58] or *consequential LCA* [58]. An attributional approach typically deals with by-products through allocation, whereas a consequential approach commonly applies system expansion [58,59]. Both approaches can be applied for retrospective and prospective purposes [60]. Both approaches have been applied in diverse ways [5], using different reference systems [3], resulting in variable results and controversies [3,60–62]. We contend that it is more important to clearly define the goal of the study and to choose the reference system that is suitable and appropriate for the goal than to categorise the LCA modelling technique.

3. Reference systems

3.1. Land reference

A structured approach for choosing a suitable land reference in bioenergy studies is illustrated in Fig. 1. Each subsection (Q1-Q4) presents a question one needs to ask when defining the goal and scope of the study. Assumptions need to be clearly stated and disclosed and care is required to ensure valid interpretation consistent with the study's goal.

Q1: Is the goal to study the absolute or relative climate effect of bioenergy system?

1a Absolute climate effect → No reference system required

The question studied by approach 1a is 'What are the absolute climate effects from the studied bioenergy system within a specified temporal window?' To answer this question, no reference system is applied. The assessment of a bioenergy system based on GHG emissions and removals which could, at least in principle, be observed and measured is consistent with the ISO Technical Specification for Carbon footprint of a product [63], LCA guidelines such as BSI [64] and WRI & WBCSD [65], and some legislation frameworks such as the EU sustainability criteria for transportation biofuels [66]. Approach 1a has been used, implicitly or explicitly, in the majority of bioenergy LCA studies [3].

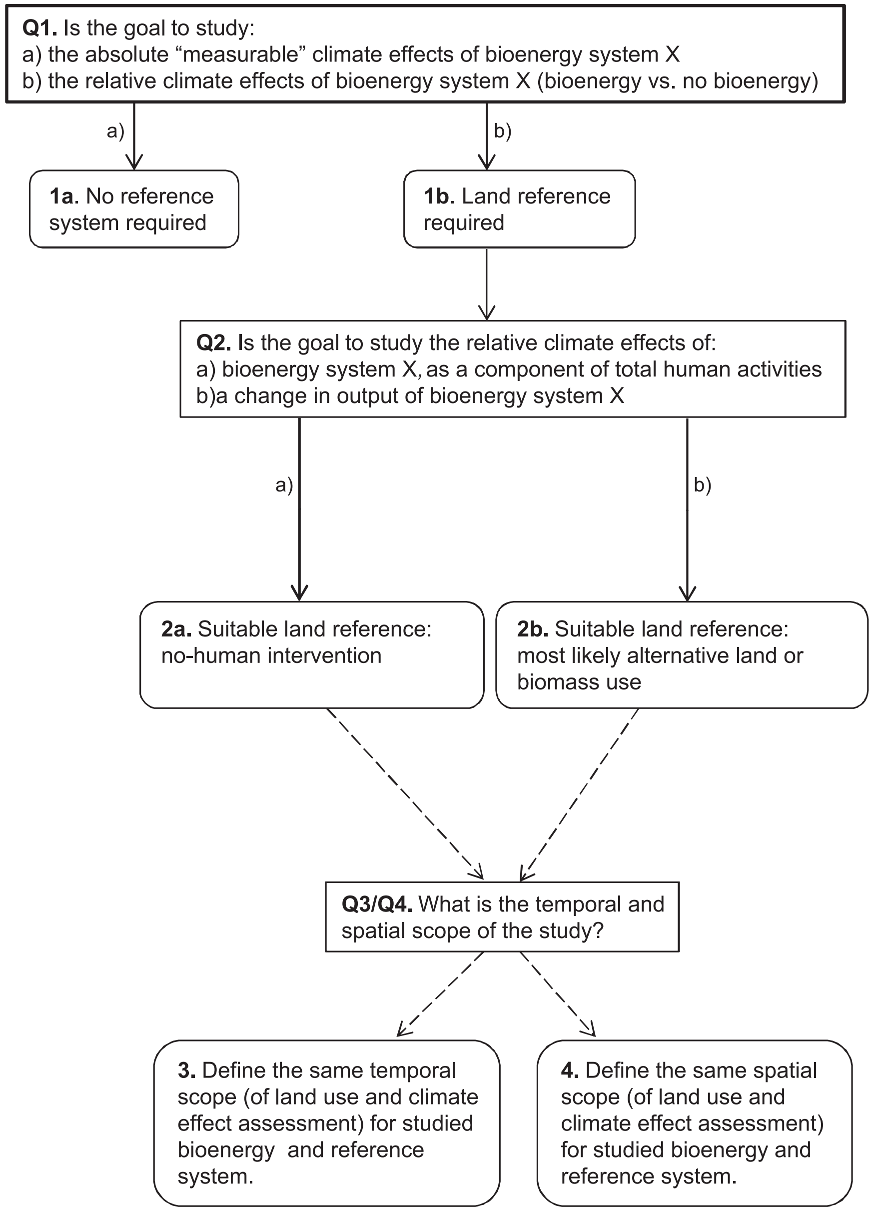

Fig. 1. A framework for defining a suitable land reference.

Absolute emissions can include the reduction in biomass and soil carbon stock from clearing native vegetation and preparing a site for agriculture or biomass production. Inclusion of the carbon loss in establishment of the bioenergy crop is equivalent to assuming a static historical baseline corresponding to the situation before the bioenergy system was established. Under approach 1a, market-mediated impacts are excluded as they require comparison to a reference scenario. Where bioenergy is one output of a multi-product system, the emissions are attributed between bioenergy and by-products using allocation.

An advantage of approach 1a is its simplicity: reference scenarios are not required and results are verifiable and easily reproduced. Assessing absolute climate effects of a bioenergy system is relevant when the goal is to follow or monitor the development, in particular GHG effects, of a bioenergy system over time or verifying the GHG effects in comparison to a predetermined threshold level (e.g. within a sustainability scheme).

The major drawback of approach 1a is that it does not capture the effects of the bioenergy system compared to what would have occurred in the absence of the bioenergy system. For example, in the absence of the bioenergy system, vegetation may have continued to grow, been used for other purposes, or been burned in-situ, each of which has a different effect on GHG emissions. Due to this drawback, approach 1a has limited applicability in assessing climate effects of bioenergy systems.

1b Relative climate effect →reference system required

When the goal is to assess the relative climate effects of a bioenergy system or introduction of, or a change in, the bioenergy system, all the effects caused by the bioenergy system studied should be considered. This is achieved by comparison with a reference system describing the situation without the studied bioenergy system. Comparing the effects of the two systems determines the 'relative climate effects' of the bioenergy system. The suitable reference system depends on the goal of the study:

Q2: Is the goal to (a) assess the relative climate effects of a bioenergy system as a component of total human activity, or to (b) consider the relative climate effects of a change in output of a bioenergy system?

2a Bioenergy as a component of total human activity → "no human intervention" reference

The question answered by approach 2a is 'How much does the studied bioenergy system contribute to total anthropogenic climate forcing within a given temporal window?' Thus, the relative climate effects of bioenergy are studied as a part of total human activity in comparison to a reference system without humans, over the same temporal window (Fig. 2). Approach 2a can provide information to estimate the share of global climate impacts that can be attributed to the studied bioenergy system and facilitate comparison of those effects to alternative systems such as fossil fuels providing functionally equivalent energy service.

2a provides a reference system to illustrate what is expected in the absence of human activities. For land, this reference is described by a natural regeneration scenario. By natural regeneration we mean the revegetation process that is expected to take place when the land is left to develop naturally, without further management, from its state at the beginning of the studied period. Changes in climate forcers and carbon stocks under a natural regeneration scenario depend on the assumed future local ecological conditions, prior management, soil quality and other characteristics. For example, carbon stocks are often assumed to increase during natural regeneration but may also decrease due to local environmental conditions. Approach 2a applies ecological models of natural vegetation growth to provide a comparison for the studied system that includes bioenergy. The natural regeneration reference was originally recommended for ALCA studies by the UNEP-SETAC Life Cycle Initiative [67] and later by Helin et al. [25] and Soimakallio et al. [3].

The advantage of approach 2a is that it provides a reference without human intervention, thus requires no assumptions about human behaviour. In approach 2a the market-mediated impacts (responses of any other anthropogenic function to the production of the studied bioenergy) are not relevant, thus omitted. This is because all the functions are considered to take place as they occur, and in the reference system there are no anthropogenic functions. Thus approach 2a does not require modelling of the market-mediated effects, which can be very challenging and is subject to significant uncertainties and sensitivities [68–70].

Limitations of approach 2a include the uncertainty of the natural regeneration reference and that it is not necessarily realistic in practice. Carbon dynamics and climate forcing associated with current vegetation, potential natural vegetation, and the regeneration pathway between current and natural states, are all uncertain. Trajectory of carbon stocks on a land area in the absence of human management depends on assumptions applied to define the prevailing global and regional conditions, as well as future conditions that involve disturbance from fire and pests, growth and decomposition rates, changing climate, and interactions with other species. It is argued that potential natural vegetation "is impossible to model" because of uncertainties surrounding ecosystem dynamics [71]. The exclusion of human activities limits the ability to compare a bioenergy system with a realistic, alternative scenario. Market-mediated effects are omitted although they could reduce or enhance climate impacts of bioenergy compared to realistic alternative scenarios [13,72,73].

When bioenergy is produced as a co-product or from biomass which is a by-product, total effects are shared between the bioenergy and other relevant products. For example, when using biomass residues such as forest residues or corn stover for bioenergy, their share of land use impacts can be allocated on the basis of energy content, mass, or economic value. The allocation basis most appropriate for the goal and scope of the study should be chosen, and it is recommended to assess the sensitivity of the results to the choice of allocation method (ISO 14044). For some secondary residues such as manure, sewage sludge or bio-waste, while it is theoretically possible to estimate their share of total land use effects, it may be difficult in practice.

2b Relative climate effects of a change in output of bioenergy → "most likely land use" reference

Approach 2b addresses the question 'What are the effects of a change in the bioenergy system over a given time horizon?' This is a common goal for studies concerned with climate change mitigation.

2b provides a reference system that incorporates human activities (i.e. anthropogenic functions are included in the reference system). The net climate consequences of increasing or decreasing bioenergy use can be studied by comparing the bioenergy system to the reference system describing the most likely alternative systems for land (Fig. 2), energy and materials. This reference system might be called 'business as usual' (BAU) if continuation of documented trends is (or was, for retrospective analysis) the most likely scenario in the absence of the bioenergy system. In prospective studies, there may be options proposed or changes expected that are different from past trends and distinct from the bioenergy option. These could be considered in alternative reference systems. Models can be employed to estimate differences in climate forcers under scenarios with and without bioenergy.

Under approach 2b, indirect effects of the bioenergy system should be captured by the analysis, as the goal is to understand all net climate effects occurring due to the differences among forcers when the bioenergy system is compared to the alternative anthropogenic reference system. Economic models can reflect indirect market-mediated effects such as substitution, market restructuring, rebound effects, and impacts on land use elsewhere (ILUC) [e.g.,74,75]. Indirect impacts may also be estimated based on empirical data from similar situations or effects documented in "natural experiments"[76]. Economic simulations allow for system expansion to handle market-mediated effects of by-products, in contrast to the allocation approach in 2a above. In principle, allocation is avoided through system expansion and inclusion of market-mediated effects such as product substitution, but in practice some allocation may be needed due to setting of system boundaries. For example, to calculate an avoided emission from substituting diesel oil by biodiesel the GHG emission intensity for diesel oil is often defined by allocating emissions between different crude-oil-based products processed in oil refineries.

The advantage of approach 2b is that it provides the most complete assessment of the climate effects occurring due to a decision about bioenergy. Information comparing a "most likely" alternative scenario to the bioenergy system is often required by policy makers, decision makers in the energy sector and land managers.

The major challenge of approach 2b is constructing the counterfactual scenario describing how things "would have been" (retrospective) or "would be" (prospective) in the absence of the bioenergy system. Consequently, the definition of appropriate system boundaries and identification of what functions are influenced by the studied change become critical issues. Economic models used to assess land system effects of bioenergy have been criticised for their uncertain results, reliance on false assumptions, and omission of critical drivers of change in land reference [50]. The most likely alternative reference system is influenced by economics, population, technology, and policy, and multiple interactions with the environment over time. Reference systems are thus always uncertain and reflect the information available to, and values of, whoever defines them. Because more than one "likely alternative" reference system is plausible, it may be informative to analyse several plausible reference systems [15,53].

The most likely alternative land reference varies between feedstocks and cases. When the bioenergy feedstock is the primary product from land use, as in the case of dedicated energy crops, the land reference is the most likely alternate way to use the particular parcel of land in the absence of bioenergy. If the bioenergy land use replaces other functions, the indirect effects due to the displacement must be considered. When the bioenergy feedstock is *not* the primary product from land use, such as for agricultural or forestry residues, the appropriate reference would describe the default land management and fate of the residues, which could be *in situ* decomposition [e.g.,36] or burning [77,78].

When secondary waste and residues (e.g. sawdust) are used for bioenergy, land management does not change and the appropriate reference system would describe the alternate fate of the residues in energy and material systems. The most likely alternate fate of feedstock should be considered in the reference system, which may include for example sawdust for animal bedding, manure for soil amendment, or tall oil for chemical products. Sometimes the alternative fate may be a different energy product, in which case the climate effect may involve market-mediated impacts. If the likely alternative disposal of the feedstock was in landfill, it could represent a carbon reservoir and a methane source [79], both of which must be taken into consideration when calculating the effects of diverting the waste to bioenergy.

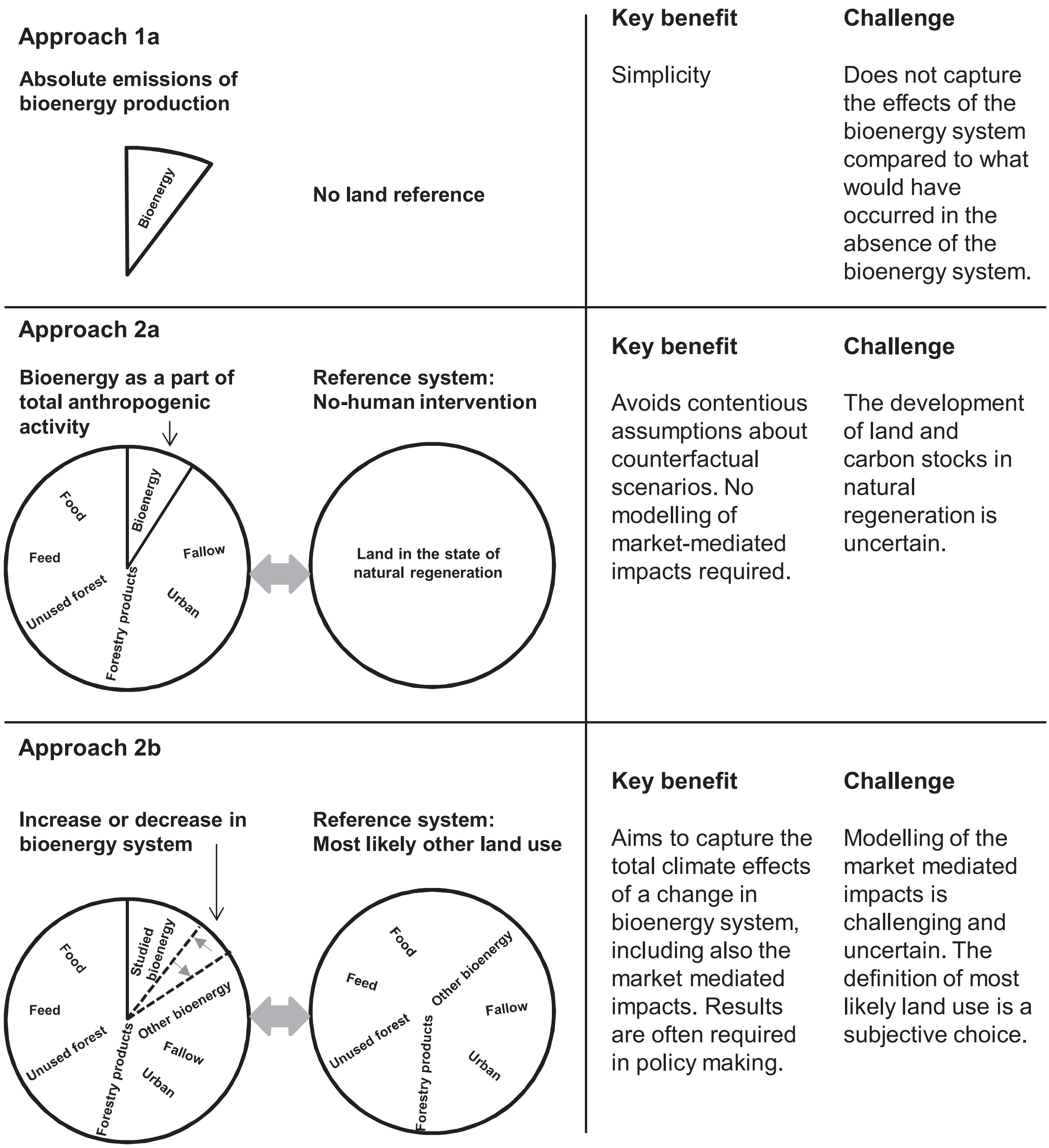

Fig. 2. Three different approaches presented; 1a: the absolute emissions, 2a: bioenergy as a component of total human activity, and 2b: a change in output of bioenergy.

Q3: What is the temporal scope for the study and timeframe for assessing climate effects?

Whether an analysis is retrospective or prospective, two distinct timeframes must be specified. First, the temporal scope for the study is defined as the period during which GHG emissions and removals and other climate forcers will be measured. This is generally the period during which the studied systems are expected to impact land resulting in climate forcing effects. Second, the timeframe over which the climate effects are quantified has to be specified (timeframe for assessing climate effects). These methodological choices influence the results and their interpretation, and should correspond with the goal and scope of the study. In the following, the importance of these choices is discussed through hypothetical examples. The temporal scope for the study and timeframe for assessing climate effects must be the same for the reference system and the bioenergy system.

Temporal scope for the study

Fig. 3 illustrates how the choice of temporal scope can influence the analysis of change in carbon stocks. Past land cover is assumed to hold carbon stocks (dashed black line). The impact of vegetation removal (vertical black line descending from dashed line) may be included in the temporal scope (Fig. 3a,b) or excluded, as a separate event occurring prior to initiating management for bioenergy (Fig. 3c,d,f) as suggested by Koellner et al. [27]. Because initial disturbance is typically triggered by multiple social and political factors, accurate attribution and allocation of cause for deforestation to bioenergy is difficult particularly if deforestation occurred many years previously, or gradually over a long period [15,49]. Fig. 3c,d,f, represent cases where the temporal scope for the study commences (T_0) following a prior land use. The end point of the study (T_1) could be when carbon stocks recover (Fig. 3a,c), or earlier points in time (Fig. 3b,d,f). The shaded area between two carbon stock scenario lines that falls between T_0 and T_1 represents the change in carbon stocks quantified in the study, and varies greatly with the choice of temporal scope. Further, as denoted by wavy lines in Fig. 3f, carbon stocks may be increasing (e.g. forest growth) or decreasing (e.g. increasing mortality or high soil respiration), depending on the case and the point in time where measurement

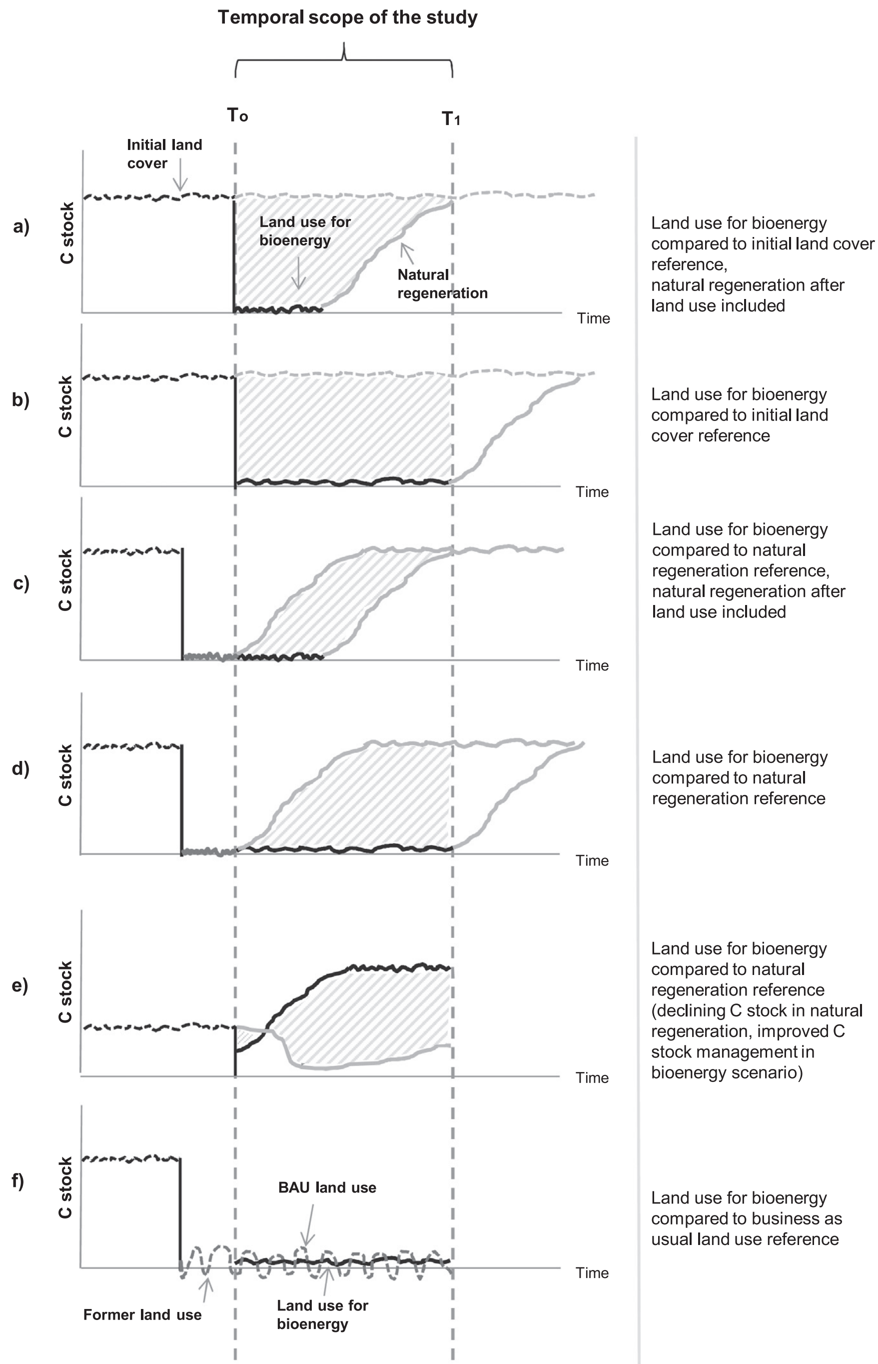

Fig. 3. Temporal scopes for studying the land system. The shaded area between T_0 and T_1 represents the change in carbon stocks quantified in the study. The natural regeneration following management for bioenergy is included (a,c) or excluded (b,d,f) in the temporal scope and corresponding differences in carbon stock quantification are illustrated. Case 3e illustrates a bioenergy system with increasing C stock due to improved management. Case f illustrates a business as usual (BAU) reference system.

begins. Such variability can lead to bias in simple BAU scenarios that only consider short term trends [17]. Fig. 3e presents an example of a bioenergy case where the carbon stock increases in the bioenergy scenario compared to reference scenario due to improved forest management, and temporary decline in the reference scenario due to e.g. pests, disease, fire and other disturbance. Forest carbon stocks may also be affected by these factors or for example by losses in soil carbon in the bioenergy scenario.

Assessments involving long rotation forest systems are especially sensitive to choice of temporal scope. The estimated change in carbon stocks depends on which phases of forest growth, harvest and regrowth are included in the study. Emission profiles and carbon stocks in land reference projections vary depending on assumptions and choice of a starting point. For example, Kline et al. [53] emphasize that “estimates of effects always depend on the reference case and many alternative future scenarios are possible.” They go on to illustrate how different reasonable reference scenarios would generate completely divergent climate-forcing results when compared to a single bioenergy scenario [53]. Buchholz et al. [80] documented how the BAU estimated by the US Forest Service at different points in the past reflected expectations of net growth or net loss of carbon stocks, depending on when the BAU started. Similarly, if forest management intensifies in the bioenergy system, relative effects depend on how long management investments continue in the future. What was considered best management at T_0

may become sub-optimal or counter-productive in the future, for example, due to improved forest management, genetic material, new competing species and pests, or changing climate or policy instruments that influence the relative value of different ecosystem services. At the end of a future forest rotation, we cannot state with certainty whether a forest will be abandoned, razed for urban development, cleared for agriculture, or continue to be managed for biomass. As the future is uncertain it is essential to clearly document assumptions and their implications on results and interpretation.

Timeframe for assessing climate effects

The timeframe for assessing climate effects is not necessarily the same as the temporal scope for the study. For example, one could evaluate cumulative radiative forcing over 100 years (consistent with the common climate metric GWP_{100}) for land management that took place within a ten-year study period. The change in temperature reached at some future point in time (e.g. 2100), estimated by the global temperature change potential GTP [81] that can be attributed to the bioenergy project may also be of interest. Regardless of which climate metrics are chosen to assess impacts [82], the assessment of climate effects starts from the same point of time as the temporal scope for the study.

Q4: What is the spatial scope for land reference and for climate change assessment?

The spatial scope of bioenergy studies can vary from global to field scale depending on the goal of the study. For example, bioenergy can be studied at a forest stand level (e.g. when defining a carbon footprint for a specific production chain) or at a national level (e.g. when studying the impacts of a national bioenergy policy aimed at intensifying forest harvest or expanding the cultivation of energy crops). The goal of the study defines if the spatial scope excludes (approach 2a) or includes (approach 2b) the indirect impacts on land use. The same spatial scope must be maintained over the temporal scale of the study for both bioenergy and reference system.

Similar to temporal scope, the spatial extent for assessing climate effects should be defined, and it is generally not the same as the spatial scope for the bioenergy and reference land use. Climate effects are usually studied at global scale. For example, one can study the global climate effects of land management in Europe. One could also be interested in local climate effects such as the impacts on local precipitation patterns associated with forest clearing in the Amazon or local temperature impacts due to changes in albedo [83,84].

3.2. Energy and materials reference

Similar to the land reference, the energy reference can be defined for current, historical or future situations, depending on the goal and scope of the study. The energy reference may reflect effects associated with industrial investments, political developments or more sustainable technologies which can be far-reaching in breadth of markets impacted, as well as long-term [85]. One of the main aims to use bioenergy, like other renewable energy sources, is to reduce consumption of fossil fuels and greenhouse gas emissions. As renewable energy becomes increasingly prevalent, the GHG intensity of the overall energy supply will decrease, and this could be significant for prospective analyses over long periods. The temporal scope may also impact on the assumptions on auxiliary energy inputs used in the bioenergy production chains.

When the goal of the study is to determine the absolute climate effects from the studied bioenergy system (aligned with approach 1a in Fig. 1) an energy reference system is not relevant. When following approach 2a (see Fig. 1), the energy reference is "no human intervention" (no energy supplied). Thus, energy reference is not applied in approaches 1a and 2a. In life cycle assessment, the climate effects associated with the use of different energy products, including bioenergy products, are studied per functional unit (e.g., 1 MJ heat delivered). This facilitates comparisons of absolute climate effects (1a) or relative climate effects (2a) of different energy products providing a functionally equivalent energy service. Typically, bioenergy is compared to fossil fuels, which currently dominate the global energy supply, representing of 81% of global primary energy use in 2014 [86].

When following approach 2b, the question becomes, "what are the effects of a change in the bioenergy system over a given time horizon?" The energy reference is the most likely energy system in the absence of the bioenergy system studied. One common method is to assume that bioenergy replaces another energy source serving the same functional unit in terms of energy. However, substitution of fossil fuels by bioenergy may lead to indirect market-mediated effects which can include both positive and negative feedback effects [73]. Interactions among policies, social preferences, relative prices and other market and non-market forces influence energy choices in both the bioenergy system and the reference system [85]. Hertwich [69] notes that emission reductions are not brought by the technologies *per se*, but by interactions of policies and society that drive behavioural change (i.e. the policies that result in fossil fuel displacement by bioenergy). These issues illustrate the complexity and uncertainties related to the energy reference. Thus, it is recommended that the uncertainties are reflected appropriately by considering several possible scenarios, as for the land reference.

The reference use of materials should be defined for significant inputs required in the bioenergy system in addition to land, biomass and energy [20,21]. Such inputs may include resources used for infrastructure (e.g., steel, concrete), fertilizers, pesticides, process chemicals, and services (e.g., repair and maintenance). Typically, a material reference system assumes that the resources would not be used or produced in the absence of bioenergy. However, similar to land and energy, market responses to changes in consumption complicate the characterization of the most likely alternative system. The impacts of the materials reference are typically minor compared to those of land and energy references.

Finally, reference systems need to account for co-products of bioenergy, such as wood products in the case of forest industry [87], animal feed in the case of crop-based ethanol or biodiesel, lignin in the case of lignocellulosic ethanol, or heat in the case of integrated FT diesel production [e.g., 88,89]. This is a complex task because there are many possibilities for substitution in markets and for most co-products considered at national or larger spatial scales, so ripple effects extend through countless additional products, each with different GHG intensities associated with its production and use [87], and their functional equivalency may be unclear [90,91]. Thus, co-product allocation methods (discussed above) are eventually necessary.

4. Uncertainties in the reference systems

Assessing the relative climate effects of a bioenergy system involves uncertainties in both the bioenergy and the reference system, especially in prospective studies since such systems cannot be verified [92]. Scenario analysis based on empirical data can inform assumptions about future projections. The spatial scale of the study influences the data requirements [93] and for regional or global analysis, average or aggregate data from FAO are often considered [94]. Energy scenarios can be informed by the official projections of IEA and IPCC.

While carbon stock changes can be estimated over time using natural vegetation models [e.g.,95], the natural regeneration land reference involves large uncertainties. Biomass productivity and carbon accumulation depend on contextual factors including slope, orientation, soils, prior land management, climate, and the frequency and intensity of disturbances [28,53]. Most parks and protected areas are actively managed to reduce impacts from disturbances so these areas may not provide an accurate reference for unmanaged lands. The increasing frequency of extreme weather events, fire, invasive species, pests and other disturbances can impact significant portions of forest in some locations; up to 25% over a decade per one recent study from the Southeast US [96]. It is impossible to accurately predict future natural disturbances and the impacts of climate change on growth and decomposition rates in natural areas. Also projections based on recent historical trends can be misleading [e.g.,68] because disturbance regimes may be large and infrequent or vary cyclically [97]. Global climate change can impact forest productivity due to raised atmospheric CO_2 concentrations, increased atmospheric nitrogen deposition, longer growing seasons, changes in rainfall patterns, higher temperatures, and the incidence and severity of disturbances due to forest fires and insect pests [98,99]. One should also specify whether anthropogenic influences on the carbon stock and growth rates, such as human-assisted regeneration or influence on fire suppression, are taken into account.

To avoid potential misinterpretations of short-term cycles, it is useful in prospective studies to consider historical trends over a time interval similar to that which the study intends to project into the future. This provides an idea of the magnitude of changes that can occur and potential cyclical behaviour in systems that could otherwise bias BAU projections [17]. A US example illustrates challenges of prospective studies: based on an analysis of periodic projections compared to actual forest dynamics in the US, Buchholz et al. [80] concluded that a fixed baseline, assuming no changes in annual growth and removals from a given point in time, would have been closer to observed data than the BAU projections which simulated anticipated rates of growth and removals.

Models, such as forest growth or energy system models, are often employed for prospective analyses [25]. To define the energy reference system, information on the current energy system can be used as a starting point. The large-scale capital investments in current energy infrastructure make it difficult to change energy systems and changes take long time. When modelling reference land use for forests, historical data, such as the age class distribution of the stands and possible changes in future growth rates and carbon stocks, e.g. due to climate change, should be taken into account. Uncertainties for land system modelling can be high due to simplifications required to represent complex systems, and low quality input data [50]. When determining and trying to minimize the uncertainty in defining the reference system, it is important to concentrate on those aspects to which the reference system is the most sensitive [6].

The uncertainty associated with defining reference systems is unavoidable because the reference scenario determines the path that was not, or will not be, followed (i.e. the counterfactual) and thus, by definition, its characteristics cannot be verified [4]. Retrospective analyses build on a higher degree of knowledge on the studied system compared to prospective analyses which attempt to project future behaviour. Because the reference system plays a fundamental role in quantifying climate effects of bioenergy, it is important to understand the sensitivity of an analysis to reference system assumptions. Impacts of some sources of uncertainty can be quantified by means of statistical approaches such as Monte Carlo simulation [e.g.,100].

5. Conclusions

In order to support informed decisions, the climate effects of bioenergy systems need to be analysed and communicated. This study provides a framework for choosing suitable reference systems for different types of research questions. For most research questions, an analysis of relative climate effects is required and a comparison with a reference system appropriate for the particular question asked is needed. We provide a process to choose and describe a reference system that is appropriate to the goal and scope of an assessment. If the goal is to study the climate effects of bioenergy as a part of total anthropogenic activity, the appropriate land reference is regeneration toward natural potential vegetation, and energy and material reference systems are not relevant. If the goal is to assess the effect of increasing or decreasing bioenergy use, the appropriate reference system incorporates human activities, and represents the expected alternative use of the land, energy, and materials in the absence of the bioenergy system being studied. Because large uncertainties surround reference systems, and these counterfactual scenarios have a decisive influence on the calculation of climate effects of a bioenergy system, several alternative reference scenarios may be considered. The assumptions made for reference systems underpinning the results of each study should always be clearly presented, and the interpretation and communication of the results should be commensurate with the constraints of the methods applied.

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