Bioenergy, Land Use Change and Climate Change Mitigation

This report was prepared by Associate Professor Göran Berndes, of Chalmers University of Technology, Sweden; with input from contributing authors Dr Neil Bird, Joanneum Research, Austria and Professor Annette Cowie, The National Centre for Rural Greenhouse Gas Research, Australia. It was co-financed by IEA Bioenergy and the Swedish Energy Agency. The report addresses a much debated issue – bioenergy and associated land use change, and how the climate change mitigation from use of bioenergy can be influenced by greenhouse gas emissions arising from land use change. The purpose of the report was to produce an unbiased, authoritative statement on this topic aimed especially at policy advisors and policy makers.

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BIOENERGY, LAND USE CHANGE AND CLIMATE CHANGE MITIGATION

Lead authors: Göran Berndes (Chalmers University of Technology)
Contributing authors: Neil Bird (Joanneum Research) and Annette Cowie (National Centre for Rural Greenhouse Gas Research)

Report for Policy Advisors and Policy Makers*

KEY MESSAGES

The sustainable use of bioenergy presents a major opportunity to address climate change by reducing fossil CO_2 emissions. Practically all bioenergy systems deliver large greenhouse gas savings if they replace fossil-based energy causing high greenhouse gas emissions and if the bioenergy production emissions – including those arising due to land use change – are kept low.

Bioenergy projects can lead to both direct and indirect land use change. The effects of indirect land use change are especially difficult to quantify and achieving a consensus on the extent of the impact is unlikely in the near future. Even so, it can be concluded that land use change can affect greenhouse gas balances in several ways, with both beneficial and undesirable consequences from bioenergy's contribution to climate change mitigation. However, bioenergy does not always entail land use change. The use of post-consumer organic residues and by-products from the agricultural and forest industries does not cause land use change if these materials are wastes, i.e. not utilised for alternative purposes.

Food, fibre and bioenergy crops can be grown in intergrated production systems, mitigating displacement effects and improving the productive use of land. Lignocellulosic feedstocks for bioenergy can decrease the pressure on prime cropping land. The targeting of marginal and degraded lands can mitigate land use change associated with bioenergy expansion and also enhance carbon sequestration in soils and biomass. Stimulation of increased productivity in all forms of land use reduces the land use change pressure.

Bioenergy's contribution to climate change mitigation needs to reflect a balance between near-term targets and the long-term objective to hold the increase in global temperature below 2ºC (Copenhagen Accord). While emissions from land use change can be significant in some circumstances, the simple notion of land use change emissions is not sufficient reason to exclude bioenergy from the list of worthwhile technologies for climate change mitigation. Sound bioenergy development requires simple and transparent criteria that can be applied in a robust and predictable way. Policy measures implemented to minimise the negative impacts of land use change should be based on a holistic perspective recognising the multiple drivers and effects of land use change.

*This report is supported by a more comprehensive 'background report' (IEA Bioenergy, 2011).

Cover Picture: *Land use in Brazil. Courtesy UNICA (Brazilian Sugarcane Industry Association).*

EXECUTIVE SUMMARY

The major opportunities to reduce fossil CO_2 emissions involve improving the efficiency with which energy is used and making the transition to alternative sources of energy and materials. These include increasing the sustainable use of biomass for the production of biomaterials, heat and power, and for transport. Two recent reports – IEA Bioenergy (2009a) and IEA RETD and IEA Bioenergy (2010) concluded that, when responsibly developed, bioenergy can make an important contribution to energy and climate policy, and can also contribute to social and economic development objectives. Even so, there is still an ongoing discussion about the role of sustainable bioenergy in the future. This concerns both environmental and socio-economic aspects, and involves a wide set of issues and many contrasting viewpoints.

This report discusses one much-debated issue, the connection between bioenergy and land use change (LUC) and especially whether there is a risk that greenhouse gas (GHG) emissions associated with LUC could significantly undermine the climate change mitigation benefits of bioenergy, and how this risk can be minimised.

Bioenergy's contribution to climate change mitigation needs to reflect a balance between near term GHG targets and the long-term objective to hold the increase in global temperature below 2°C (Copenhagen Accord). Sound bioenergy development requires adequate and transparent criteria that can be applied in a robust, predictable way. Incentives should discourage systematic decreases in biospheric carbon stocks while encouraging the sustainable use of biomass to substitute fossil fuels instead of decaying unutilised.

There are a number of options that society can choose to ensure that the benefits of bioenergy can be realised while taking into account LUC issues. These are:

- Promote only bioenergy options that meet set requirements with respect to LUC, e.g. use bioenergy which is certified to have avoided undesirable LUC, or met target GHG reduction thresholds when LUC is taken into account.
- Assign a certain level of LUC emissions to bioenergy options, depending on their land use replacement. It might be advisable to allow producers who are close to eligibility requirements to acquire and retire emission rights as a way of complying with the requirements rather than exclude them from the market, or allow other 'offsets'.
- Support development of bioenergy options that have smaller LUC risks, such as biomass production on degraded or other marginal lands, integrated biomass/food/feed production, and the use of residues, waste and bioenergy plants that can avoid competition for prime cropland.
- Shape GHG accounting policies to encourage low-LUC bioenergy. For example, carbon neutral status could be applied only to bioenergy produced and consumed in countries that include LUC and forest management emissions/removals in GHG accounting.
- Promote an integrated and international approach among energy, agriculture, and development policies to stimulate much-needed agricultural productivity increases in the developing world.
- Promote climate friendly alternatives in addition to bioenergy, although this may be a particular challenge in the transport sector where it is likely to be some decades before such alternatives become established on a substantial scale.

Depending on their implementation, the above options for addressing bioenergy-driven LUC may not be able to avoid indirect GHG emissions completely, due to the interconnectedness of the agricultural and forestry systems. In the longer term, a global GHG emissions cap that regulates both fossil and biospheric carbon emissions could be one option providing flexibility. Countries may then decide to use a certain share of their permitted emission space to develop a bioenergy industry to secure long-term domestic energy supply, or to generate export revenues.

While emissions from LUC can be significant in some circumstances, the simple notion of LUC emissions is not sufficient reason to exclude bioenergy from the list of worthwhile technologies for climate change mitigation. Sound bioenergy development requires simple and transparent criteria that can be applied in a robust and predictable way. Policy measures implemented to minimise the negative impacts of LUC should be based on a holistic perspective recognising the multiple drivers and effects of LUC, and taking into account the dynamics of both energy and climate systems.

Climate Change Mitigation

The GHG savings associated with specific bioenergy options depend on what fossil fuels they are replacing, the geographical location, and the design of the bioenergy system. The precise quantification of GHG savings for specific systems is often hampered by lack of reliable empirical data. Furthermore, alternative methods of quantification lead to variation in estimates of GHG savings.

Nonetheless, it is possible to conclude that practically all bioenergy systems deliver large GHG savings if they replace fossil-based energy causing high GHG emissions and if the bioenergy production emissions – including those arising due to LUC – are kept low. Efficient fertiliser strategies (minimising emissions of N_2O, which contributes to global warming) and the minimisation of GHG emissions from the biomass conversion process are essential.

Land Use Change

Changes in land use, principally those associated with deforestation and expansion of agricultural production for food, contribute about 15% of global emissions of GHG. Currently, less than 1% of global agricultural land is used for cultivating biofuel crops and LUC associated with bioenergy represents a very small percentage of overall changes in land use. However, given that reducing emissions is one important driver for bioenergy, policy makers are understandably concerned that the impacts of LUC are properly taken into account when planting more energy crops is being contemplated or incentivised.

Bioenergy projects can lead to both direct and indirect LUC.

- Direct LUC (dLUC) involves changes in land use on the site used for bioenergy feedstock production, such as the change from food or fibre production (including changes in crop rotation patterns, conversion of pasture land, and changes in forest management) or the conversion of natural ecosystems.
- Indirect LUC (iLUC) refers to the changes in land use that take place elsewhere as a consequence of the bioenergy project. For example, displaced food producers may re-establish their operations elsewhere by converting natural ecosystems to agriculture land, or due to macro-economic factors, the agriculture area may expand to compensate for the losses in food/fibre production caused by the bioenergy project. A wide definition of iLUC can include changes in crop rotation patterns and/or intensification on land used for food or feed production.

LUC can affect GHG emissions in a number of ways, for example:

- when biomass is burned in the field during land clearing;
- when the land management practice is changed so that the carbon stocks in soils and vegetation change;
- when changes in the intensity of land use lead to changes in GHG emissions, in particular N_2O emissions due to fertiliser use; and
- when LUC results in changes in rates of carbon sequestration, i.e. the CO_2 assimilation of the land may become lower or higher than would have been the case in the absence of LUC.

The impacts of these changes can increase the net GHG emissions (for example when land with large carbon stocks is brought into cultivation) or have a beneficial outcome (for example when perennial crops replace annual crops grown with high fertiliser levels, or where energy crops are developed on marginal lands with carbon-poor soils).

LUC may also influence the extent to which the land surface reflects incoming sunlight. This reflectance is referred to as albedo. Such changes in albedo may influence global warming. In regions with seasonal snow cover or a seasonal dry period (e.g. savannas), reduction in albedo due to the introduction of perennial green vegetative cover can counteract the climate change mitigation benefit of bioenergy. Conversely, albedo increases associated with the conversion of forests to energy crops (e.g. annual crops and grasses) may counter the global warming effect of CO_2 emissions from the deforestation.

Bioenergy does not always entail LUC. The use of post-consumer organic residues and by-products from the agricultural and forest industries does not cause LUC if these biomass sources are wastes, i.e. were not utilised for alternative purposes. Biomass that is burned – such as straw on fields or natural vegetation during forest clearing – are obvious examples. The use of biomass that would otherwise be landfilled, or decompose in wet conditions, can also lead to additional benefits through reduced methane emissions. If not utilised for bioenergy, some biomass sources (e.g. harvest residues left in the forest) would retain organic carbon for a longer time than if used for energy. This difference in timing of emissions can be considered a disbenefit for bioenergy in evaluations which only use a short-time horizon and also a relevant factor in longer term accounting in regions where biomass degradation is slow.

Bioenergy feedstocks can be produced in combination with food and fibre, avoiding land use displacement. The targeting of unused marginal and degraded lands can also mitigate LUC emissions associated with bioenergy expansion. Wisely designed, located, and managed bioenergy plantations can improve the productive use of land and can provide benefits in addition to GHG savings, such as reduced erosion, reduced eutrophication, improved biodiversity, and improved socioeconomic conditions in the areas where bioenergy production expands.

One promising way of reducing emissions from LUC is to increase the amount of lignocellulosic feedstocks for bioenergy that are grown on low carbon pasture land less suitable for annual crops, thereby decreasing the pressure on prime cropping land. Since the production of lignocellulosic feedstocks commonly requires less fuel, fertiliser and other inputs, there is also scope for higher GHG savings than when biofuels are produced from conventional crops such as cereals and sugar beet. However, a mix of lignocellulosic material and conventional food/feed crops is likely to be used as bioenergy feedstocks during the coming decades to supply biofuels and the heat and power markets. Strategies to increase agricultural productivity, especially in developing countries, will be critical to minimising LUC impacts. In general, stimulation of increased productivity in all forms of land use reduces the LUC pressure.

Effects of Land Use Change on Greenhouse Gas Savings

The GHG effects of LUC are difficult to quantify with precision in relation to a specific bioenergy project, particularly for iLUC where the causes are often multiple, complex, interlinked and change over time. Despite the significant uncertainties involved in the quantification of LUC effects of a specific bioenergy project, it can be concluded that LUC can significantly influence the climate change mitigation benefit of bioenergy – in both positive and negative directions.

Some bioenergy projects cause very large LUC emissions and these will not contribute positively to climate change mitigation within relevant time horizons. The clear-felling and drainage of peat swamp forests to establish oil palm plantations is one example. On the other hand, the establishment of bioenergy plantations can also lead to assimilation of CO_2 into biomass and soils, and this enhances mitigation benefits. One example is the reforestation of degraded land that has carbon-depleted soils and sparse vegetation. An additional benefit in this case is that the soil quality, and therefore productivity, can improve over time given appropriate plant selection and land management.

When bioenergy expansion causes increases in LUC emissions, the negative impact is usually greatest in the near term and the cumulative net GHG savings then improve over time as the savings from fossil fuel replacement accumulate.

The overall net emissions savings may therefore be subject to a time lag, and this needs to be taken into account in considering the role of biofuels, for example, as one of the few near term options for climate change mitigation in the transport sector. However, biofuels can be considered a useful measure to reduce GHG emissions even if net savings are not always instantly achievable. Their long-term contribution can become especially important in a scenario where the alternative is to produce transport fuels based on unconventional oil and coal, without employing carbon capture and storage (CCS) technologies. Furthermore, meeting ambitious climate targets will also require climate-friendly fuels in air and marine transport where no alternative to biofuels is currently available.

Bioenergy's Contribution to Climate Stabilisation

Climate targets set limits on future GHG emissions. In order to stabilise the concentration of GHGs in the atmosphere, emissions need to peak and decline thereafter. Many different emission trajectories are compatible with a given stabilisation target. Mitigation efforts over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels. Drastic changes in the global energy system are needed. However, the establishment of the required new energy technologies and associated infrastructure will in itself lead to GHG emissions, implying that a portion of the 'emission space' allowed within the GHG target will need to be 'invested' for energy system transformation. For example, electric vehicle fleets may contribute to increasing atmospheric CO_2 levels as long as electricity is mainly generated from fossil fuels. However, promotion of electric vehicles can be justified because they will be able to provide efficient transport services that cause low GHG emissions if nations can overcome the challenge of modifying their electricity matrix towards cleaner energy sources, relying less on fossil fuels.

Similarly, some level of LUC emissions associated with bioenergy expansion may be an acceptable *temporary* consequence of the establishment of an industry capable of providing long-term renewable and climate-friendly energy services for the world. The GHG emissions associated with bioenergy will decrease over time as above-ground biomass and soil carbon stabilise at new equilibrium levels, conversion technologies improve and use renewable sources for process fuel, and feedstock production systems become less GHG-intensive. Should CCS technologies become available, bioenergy is the only currently available energy technology that – combined with CCS – allows net removal of CO_2 from the atmosphere, making it pivotal for achieving ambitious climate protection targets should the peak in GHG emissions occur late.

Bioenergy and Land Use Change in a Wider Context

Climate change mitigation is not the only issue that needs to be considered when assessing the merits of bioenergy. Other important aspects include security of energy supply, job creation and income generation, and consequences for biodiversity, water, and soils. Also, it is important to note that climate change mitigation is just one of many rationales for ecosystem protection. Measures to reduce emissions due to LUC may encourage LUC on low-carbon stock lands, such as natural grasslands. While this may have a small impact in terms of climate change mitigation, it may impact negatively on biodiversity and water tables. Land owners may also see a net profit from converting relatively high-carbon stock land to high productivity bioenergy plantations even if this incurs additional carbon payment costs due to initial LUC.

As stated above, improving agricultural productivity is an important way of reducing LUC pressure. But minimising future LUC rates will also depend on the establishment of sustainable land use practices when agriculture expands into new areas. In some places removal of natural vegetation to establish agriculture leads to only short-term benefits, which are followed by land degradation and low productivity, in turn leading to the need for further land conversion. The application of established best practice and mixed production systems can sustainably increase land productivity. These measures are not applied in many developing countries at present because of a lack of information dissemination, capacity building, and access to capital and markets. Economic pressure to maximise short-term returns may also make landholders in industrialised countries reluctant to apply sustainable techniques that would result in a short-term yield penalty.

As has been described above, bioenergy production interacts with food and forestry production in complex ways. It can compete for land, water and other resources but can also strengthen conventional food and forestry production by offering new markets for biomass flows that earlier were considered waste products. Bioenergy demand can provide opportunities for cultivating new types of crops and integration of bioenergy production with food and forestry production in ways that improve overall resource management. It can also lead to over exploitation and degradation of resources.

Bioenergy development ultimately depends on the priority of bioenergy products versus other products obtained from land – notably food and conventional forest products – and on how much biomass can be mobilised in total from agriculture and forestry. This in turn depends on natural factors (e.g. climate, soils, and topography) and on agronomic and forestry practices employed to produce the biomass, as well as how society understands and prioritises nature conservation and soil/water/biodiversity protection and how the production systems are shaped to reflect these priorities.

INTRODUCTION

There is at present a lively public debate, as well as substantial scientific activity related to the sustainability of bioenergy, and in particular the sustainability of liquid biofuels. The debate concerns both environmental and socio-economic aspects, and involves a wide set of issues and many contrasting viewpoints.

This report concerns one much-debated issue – bioenergy and associated land use change (LUC), and how the climate change mitigation from use of bioenergy can be influenced by greenhouse gas emissions (GHG) arising from LUC. Both biofuels for transport and biomass use for heat and power are considered. Also considered are present and prospective fossil fuel substitution patterns, including for example, the substitution of fossil transport fuels such as coal-based Fischer-Tropsch diesel.

An investigation of how LUC can influence carbon (C) flows and the net GHG reduction benefits of bioenergy requires consideration of:

- GHG emissions from the bioenergy chain, and
- changes in GHG emissions due to the displacement of fossil-based energy and other products with bioenergy and co-products from its production.

The quantification of GHG emissions is treated concisely in this report by synthesising up-to-date original research and literature reviews. Readers are referred to other publications for more in-depth information concerning methodology and uncertainties in quantifications of GHG emissions (see, e.g. JRC 2007; WBGU 2009; Cherubini *et al.* 2009; and IEA Bioenergy Task 38 2010).

In addition to the GHG implications of LUC for bioenergy there are other important considerations – such as biodiversity, hydrology, and socio-economics. However, these are not covered in detail in this report. The report does not consider aquatic biomass.

THE CARBON CYCLE

The world has five principal C pools – fossil resources, the atmosphere, the ocean, the biosphere containing all ecosystems, and the pedosphere, which is the free layer of soils above the bedrock. The fossil and biospheric C pools differ in their interaction with the atmospheric C pool. There are large bi-directional flows between the atmosphere and the biosphere. These vary from year to year; they are difficult to quantify, and are expected to be influenced by climate change in ways not yet well understood. In contrast, the flow of C from the fossil pool to the atmosphere that is caused by the use of fossil fuels is one-directional on relevant time scales and well quantified.

Part of the C that is emitted to the atmosphere is taken up by the ocean and part is assimilated in the biosphere due to reforestation in some parts of the world and the 'CO_2 fertilisation effect' that stimulates plant growth. Forests in Europe and North America, for example, presently function as a C sink. There are options for enhancing the biospheric assimilation of atmospheric C, such as afforestation of sparsely vegetated areas.

Forestry and agriculture management options for assimilation of atmospheric C, e.g. reforestation and cropland management to increase soil C content, can provide additional benefits

Figure 1. Forested walking trail along Etobicoke Creek in Mississauga, Ontario. Forests maintain critical functions in the biosphere and afforestation can lead to many benefits including C sequestration. Afforestation is a commonly proposed option for climate change mitigation. However, depending on the conditions, establishment of bioenergy plantations may be the preferred land use option for climate change mitigation. It is essential that the development of LUC strategies for climate change mitigation reflect the local context, i.e. the societal aspirations and priorities in relation to supply and demand for food, energy services, and material products – considering also the economic, security and environmental implications. Photo courtesy of Brent Perry.

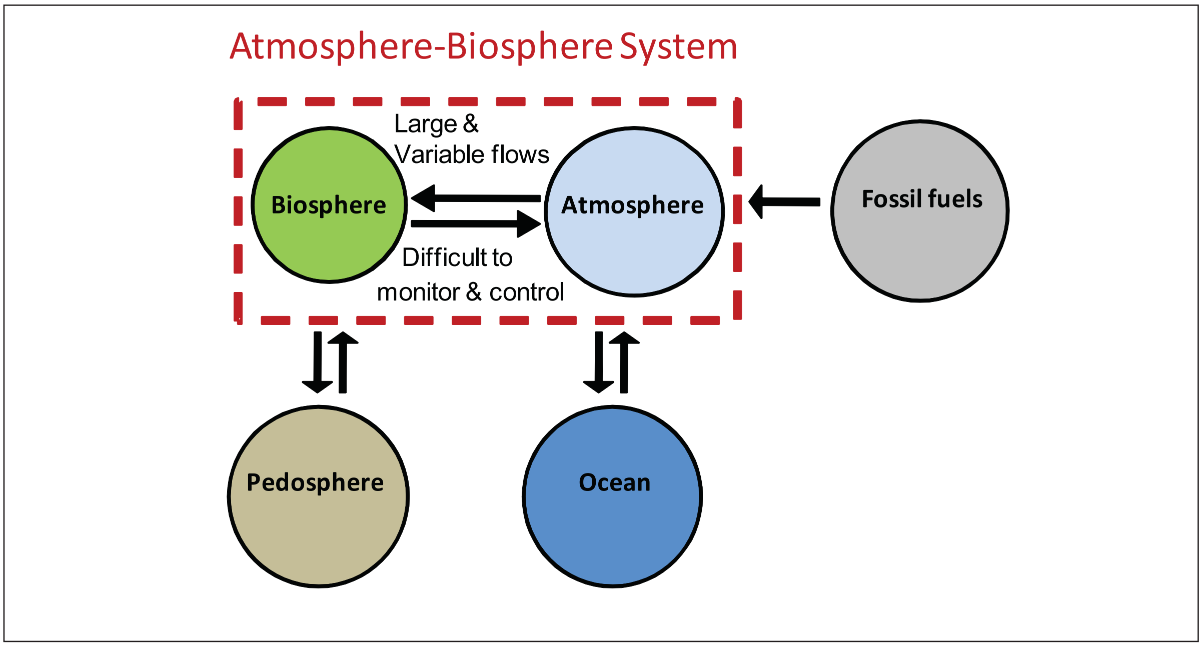


Figure 2. The five principal C pools. The atmosphere-biosphere system is characterised by large bi-directional flows between the atmosphere and biosphere, which are highly variable from year to year, difficult to quantify, and expected to be influenced by climate change in ways not yet well understood. Atmospheric C can – at least temporarily – be re-allocated to the biosphere, but this does not solve the problem of climate change, which mostly is caused by the transfer of fossil C into the atmosphere-biosphere system.

such as biodiversity preservation and improved soil and water quality. However, they do not represent a long-term, permanent solution to the problem of increasing atmospheric C concentrations since their assimilation capacity is too small. The long-term integrity of biospheric C sinks is also uncertain since they are sensitive to socio-economic and environmental factors, including fires and future LUC. Additionally there are concerns over the biodiversity impacts of reforestation with exotic monocultures, where reforestation is aimed purely at C sequestration.

There are options for removing C from the atmosphere and storing it in other pools for a long time. These include technologies for capturing C directly from ambient air and storing it in geological reservoirs, as well as various means of accelerating geochemical weathering to remove C from the atmosphere and store it in stable carbonates or bicarbonates. These options are at an early stage of development and there are significant uncertainties regarding their practical and economic applicability on scales large enough to make a significant contribution to climate change mitigation.

In order to address concerns about rising atmospheric C levels, emissions of fossil C to the atmosphere need to be reduced (Figure 2). The major options for achieving this include reducing energy use and moving to lower carbon energy technologies including renewable energy. Increased supply of sustainable bioenergy can play an important role.

BIOMASS RESOURCES

Biomass (mainly wood) presently contributes some 50 EJ/year, or 10% of the global primary energy supply and is the most widely used renewable energy source (Figure 3).

A major part of present biomass use (about 80%) is the so-called 'traditional bioenergy use', i.e. the use of charcoal, wood, and manure for cooking, space heating and lighting, generally by poorer populations in developing countries. The smaller, 'modern' bioenergy use (for industry, power generation, or transport fuels) makes a significant contribution, however, and its share is growing rapidly.

Studies of the future global biomass supply potential indicate that it should be possible to produce several hundred EJ/year of biomass for energy by 2050 while taking into account sustainability constraints. Forest and agricultural residues and other organic wastes could provide in the order of 100 EJ/year and substantially larger volumes could be provided from presently unutilised forest growth and from dedicated biomass plantations, given positive agricultural productivity growth. Thus, bioenergy can significantly increase its existing contribution to policy objectives, such as CO_2 emission reductions and energy security, as well as to social and economic development objectives.

But realising high potentials requires far-reaching changes in present land use. Providing several hundred EJ/year from bioenergy plantations will require the planting of several hundred million hectares of land with energy crops. Similarly, far-reaching changes in forest management will be required to provide forest wood in the volumes assessed as potentially available in the future.

The way that forest bioenergy develops and biomass plantations are established will determine whether – and to what extent – bioenergy expansion leads to biospheric C losses or gains through LUC, and this can significantly influence the overall climate change mitigation benefit of bioenergy expansion.

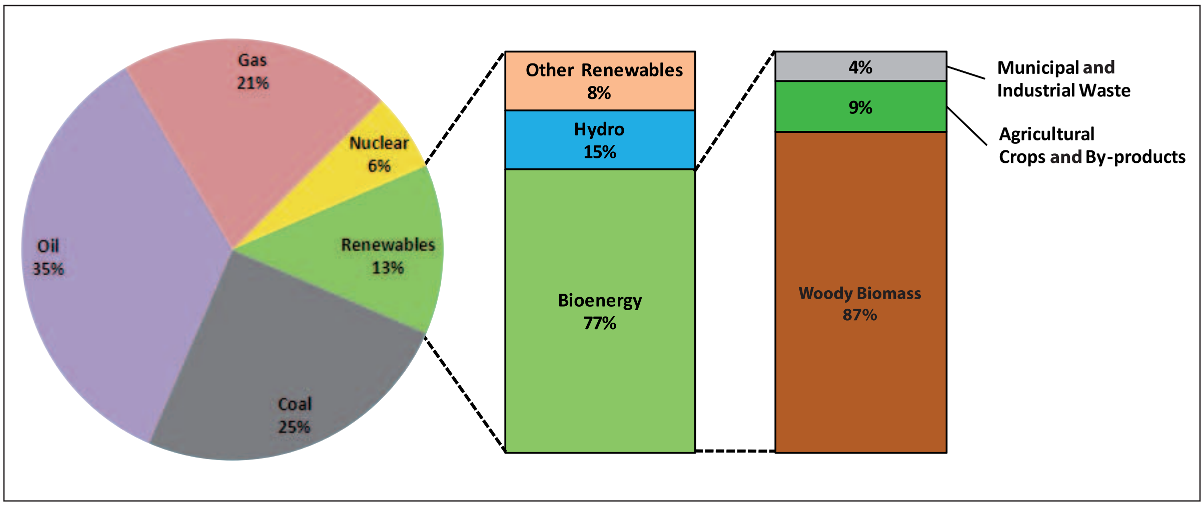


Figure 3. Share of bioenergy in the global primary energy supply. For further information, see IEA Bioenergy, 2009a.

LAND USE CHANGE

Figure 4 shows the accumulated anthropogenic C emissions to the atmosphere since 1850. LUC emissions – primarily associated with the conversion of forests to agricultural land – have contributed roughly one-third during this period. Carbon emissions due to fossil fuel use now represent the largest source and at present are more than five times larger than the LUC emissions.

Agricultural expansion has been, and continues to be, one major driver of LUC and the associated emissions. Energy-related projects also play a role. Hydropower projects can submerge large areas and also cause methane emissions due to the anaerobic decomposition of the submerged vegetation.

Surface mining of coal, onshore oil and gas projects, and also exploitation of unconventional fossil resources, can cause deforestation or other land conversion for access roads, drilling platforms, and pipelines. In addition, the easier access to previously remote primary forest provided by new roads and pipeline routes can lead to increased logging, hunting, and deforestation for human settlement. Nevertheless, LUC is to a greater extent linked to bioenergy because of its close association with agriculture and forestry.

Currently, less than 1% of global agricultural land is used for cultivating biofuel crops and LUC associated with bioenergy represents a very small percentage of overall changes in land use. However, bioenergy is the primary energy source most closely associated with large-scale land use change. Policy makers and other stakeholders have therefore particularly

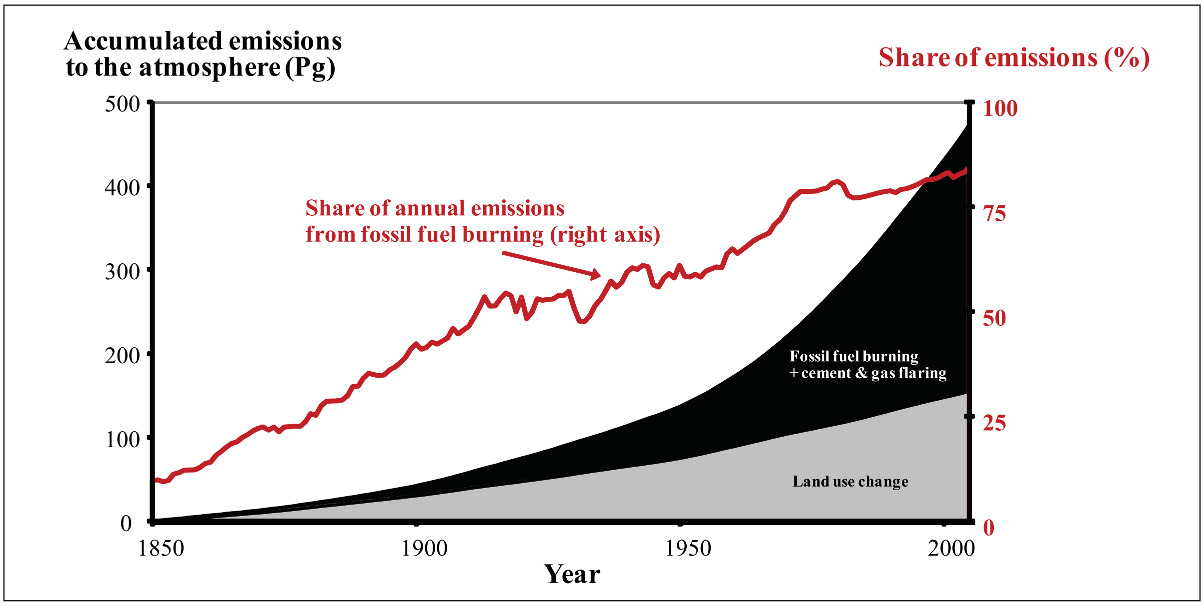


Figure 4. Accumulated anthropogenic C emissions to the atmosphere since 1850. Data source: The Carbon Dioxide Information Analysis Center (CDIAC) of the US Department of Energy (DOE).

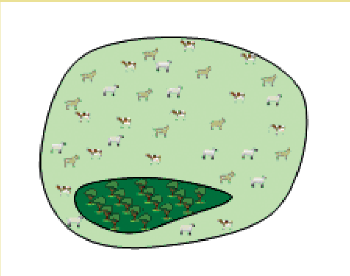
focussed attention on how LUC emissions affect the climate benefit of increasing levels of bioenergy.

It is common to distinguish between direct and indirect LUC (Figure 5).

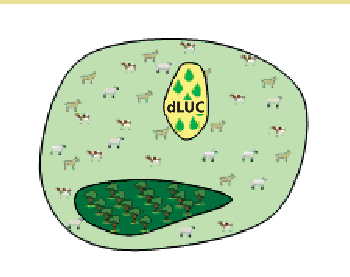
- Direct LUC (dLUC) involves changes in land use on the site used for bioenergy feedstock production, such as the change from food or fibre production (including changes in crop rotation patterns, conversion of pasture land, and changes in forest management) or the conversion of natural ecosystems.
- Indirect LUC (iLUC) refers to the changes in land use that take place elsewhere as a consequence of the bioenergy project. For example, displaced food producers may re-establish their operations elsewhere by converting natural ecosystems to agriculture land, or due to macro-economic factors, the agriculture area may expand to compensate for the losses in food/fibre production caused by the bioenergy project. A wide definition of iLUC can include changes in crop rotation patterns and/or intensification on land used for food or feed production.

LUC emissions arise when biomass is burned during land clearing, or when the land management practice is changed so that above-ground and/or soil C stocks decrease. Intensified land use may also lead to increased GHG emissions, in particular N_2O emissions.

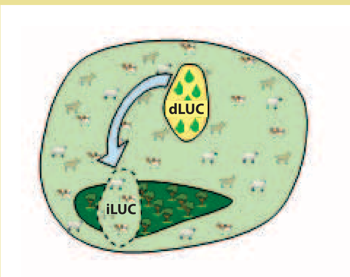
But LUC associated with a bioenergy project can also lead to the assimilation of atmospheric CO_2 into the biosphere, enhancing GHG emissions reduction. Examples of this include the conversion of degraded land to woody plantations and also the planting of perennial herbaceous plants and short rotation woody plants on agricultural land. Figure 6 presents one illustrative case showing how the affected C pools change over time.



Before introduction of the bioenergy production the land base is a mixture of grazing and forest land.



The introduction of the bioenergy production on grazing land is direct land use change (dLUC) and may cause a loss of soil organic carbon (i.e. an emission). If the bioenergy production is introduced on forest land, then the dLUC may be large because there is also a loss of forest biomass (including litter and dead wood). If the production is introduced on existing cropland then the dLUC will be smaller.



Macro-economic pressures cause an increase in the value of grazing animals (i.e. meat). This creates an incentive for a land owner (not necessarily the owner of the land that was converted to bioenergy production) to convert a portion of the forest land to grazing land. This is indirect land use change (iLUC) and causes a loss of forest carbon stocks (including litter, dead wood and soil) which is an emission.

The iLUC may occur instantaneously with the introduction of the bioenergy production or may be delayed by some period of time. If the bioenergy production was introduced on cropland, then both grazing land and forest land may be converted to replace the lost crop production.

There need not be a one-to-one relationship between the pasture/cropland area converted to bioenergy and the area converted to new pasture/cropland. This relationship depends on the relative productivity of the old vs. new pasture/cropland and to what extent the macro-economic pressure induces increased productivity.

Figure 5. Examples of direct and indirect land use changes arising as a consequence of a bioenergy project.

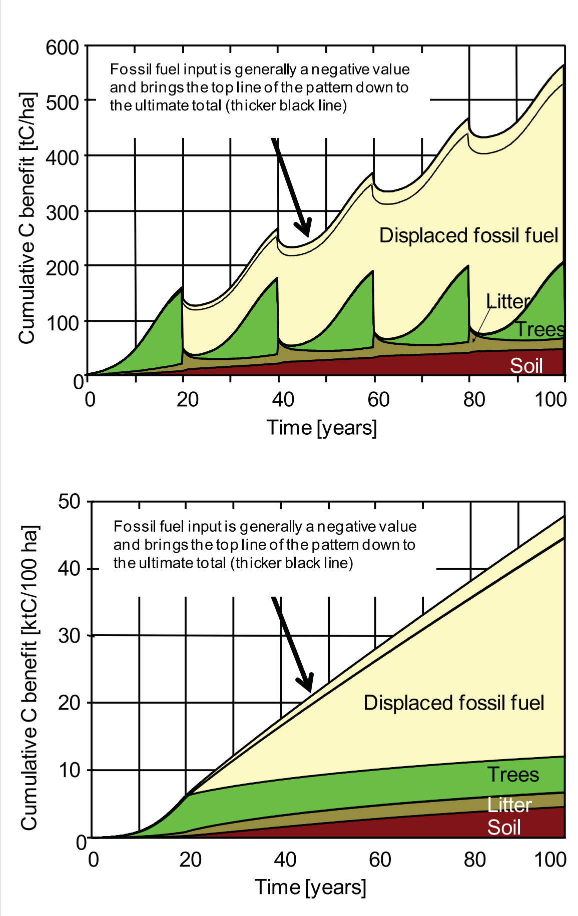


Figure 6. Reforestation (year one) of sparsely vegetated land having relatively low soil C level, with subsequent use of the harvested biomass for energy. The cumulative climate benefit is shown on the 1-hectare stand level (top) and on the 100-hectare landscape level – i.e. a plantation system producing a constant stream of biomass (bottom). As can be seen, the longer term climate benefit is dominated by the fossil fuel displacement but the C build-up in soils, litter and trees contribute substantially. Note that this example excludes the possible consequences of the iLUC that might arise due to reforestation. Diagrams produced using the GORCAM model (*http://www.joanneum.at/gorcam.htm*).

Bioenergy does not always cause LUC. The use of post-consumer organic waste and agricultural/forest industry by-products can avoid land use change and related greenhouse gas emissions. However, if these biomass sources were previously used for other purposes, LUC effects can still arise as the previous users switch to using new raw materials. Over-exploitation of harvest residues may result in decreasing soil productivity and lower yields leading to cropland expansion to compensate for the lost production. The dynamics of terrestrial carbon stocks in LUC and long-rotation forestry leads to GHG mitigation trade-offs between biomass extraction for energy use and the alternative to leave the biomass as a carbon store that could further sequester more carbon over time. If not utilised for bioenergy, some biomass sources (e.g. harvest residues left in the forest) would retain organic carbon for a longer time than if used for energy. Such delayed GHG emissions can be considered a benefit in relation to near-term GHG targets and also be a relevant factor in longer term accounting in regions where biomass degradation is slow (e.g. boreal forests). However, fires, insect outbreaks, and other natural disturbances can convert forests from net sinks to net sources of GHG. In forest lands susceptible to periodic fires, good silviculture practices can lead to less frequent, lower intensity fires, and enhance forest growth rates and soil carbon storage. Using biomass removed in such practices for bioenergy can provide GHG and particulate emission reductions by utilising biomass that might otherwise burn in open air forest fires. Furthermore, deposited organic wastes may cause methane emissions as they decompose, leading to a greater climate impact than if burned directly, albeit with a different time profile.

The production of biomass for energy can also be integrated with the existing land use, and ideally stimulate increased productivity and in this way avoid land use displacement (see section 'Options for Mitigating LUC Associated with Bioenergy'). Mixed production systems (double-cropping, crop with livestock and/or crop with forestry) hold the potential to improve land and water productivity as well as carbon sequestration, and to improve food security and resource use efficiency. Integration can also occur at the feedstock conversion level – typically producing animal feed that can replace cultivated feed such as soy and corn and so also reduce grazing requirements.

CLIMATE CHANGE MITIGATION

The contribution of bioenergy systems to climate change mitigation should be evaluated by comparing their influence on global warming with the influence of the energy systems they replace. Figure 7 outlines a standard methodology framework for such evaluations that has been developed by IEA Bioenergy Task 38. It employs methodologies in line with the ISO 14040:2006 and 14044:2006 standards for Life Cycle Assessments (LCA) which define the principles, framework, requirements, and guidelines for conducting an LCA study.

Critical steps include system definition (spatial and dynamic system boundary), definition of functional unit, reference flows and indicators, and the selection of allocation methods for energy and material flows that cross the system boundary. The handling of spacial and temporal variation and uncertainty related to data used may have significant impact on the results.

Figure 7 shows a general scheme for comparing bioenergy and fossil energy systems. IEA Bioenergy Task 38 has developed a standard methodology framework for evaluating the GHG balance of bioenergy systems. Important aspects of the Task 38 methodology include the requirements that:

- the reference and bioenergy systems must deliver equivalent service;
- the alternative use of the land must be included in the reference case;
- by-products should be included within the boundaries of the studied system;

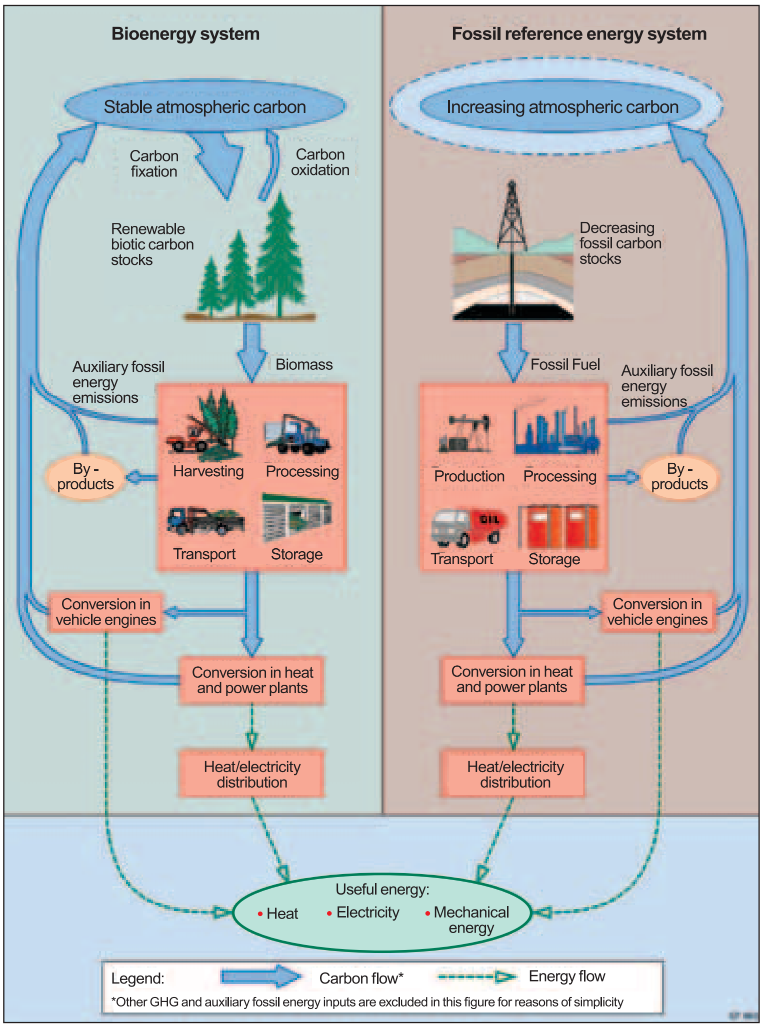


Figure 7. How to compare bioenergy and fossil energy system. For further information, visit *www.ieabioenergy-task38.org*

- the appropriate reference energy system is that which the bioenergy system displaces;
- the fossil fuel emissions displaced will be affected by the relative efficiencies of the energy conversion technologies and carbon dioxide emitted per unit of energy;
- leakage should be acknowledged and estimated – iLUC is one example of leakage and others include increase in total energy usage as a result of greater energy availability;
- non-CO_2 GHGs should be included in estimates of emissions and removals from bioenergy and reference cases; and
- the result should be expressed in the appropriate functional units – emissions reduction per land area for purpose-grown biomass, or per unit of biomass for residues.

One challenge experienced is that it has been difficult to obtain comparable LCA data for the reference energy system replaced – ideally these LCA data should come from studies with consistent methodologies, scope, level of detail, and country representativeness. Also the possible LUC associated with these replaced energy systems needs to be considered in the evaluation. This adds to the challenge since LUC effects – especially iLUC associated with fossil and other conventional energy supply – have not been studied extensively.

Studies that compare specific bioenergy options with other energy options need to be complemented with more comprehensive analyses using integrated energy/industry/land use cover models that describe how an expanding bioenergy sector interacts with other sectors in society, including competing energy supply technologies and other options for meeting climate/energy and other policy objectives, plus land use and management of biospheric C stocks. Such analyses can give insights into aspects that cannot be investigated by evaluating individual options separately. One example is the importance of up-front LUC emissions in the context of global climate targets and development pathways towards complying with such targets. This is discussed later in the report (see section '*Bioenergy and LUC in the Context of Global Climate Targets*').

GHG Emissions Reduction in the Absence of LUC

Figure 8 shows ranges in estimated GHG emissions for a number of bioenergy options, when the effects of possible associated LUC are not included. As noted above, quantification of GHG emissions involve many uncertainties. A wide range of results has also been reported for specific bioenergy options.

Variations may be attributed to actual differences in the systems being modelled. Results need to be understood in the context of specific locations taking the natural conditions and industrial capacity into account. However, variations can also be caused by methodology differences and by differences in the data used to characterise a given process. For example, crediting for avoided emissions from waste or residues (such as methane from landfills) can significantly change the emissions profile of bioenergy systems using such resources.

Studies of prospective bioenergy options (e.g. biofuels derived from lignocellulosic biomass) require projections of performance for technologies that are not yet mature and therefore have greater associated uncertainties in the absence of information from full-scale commercial operation.

In addition, many biofuel production processes create multiple products. Bioenergy systems can be part of biomass cascading cycles in which co-products and biomaterials themselves are used for energy after their useful life. This introduces significant data and methodological challenges, including consideration of space and time aspects, since GHG emissions and other environmental effects can be distributed over decades and different geographical locations. Nevertheless, despite these uncertainties several conclusions can be drawn. One conclusion is that, contrary to some negative reports, biofuels

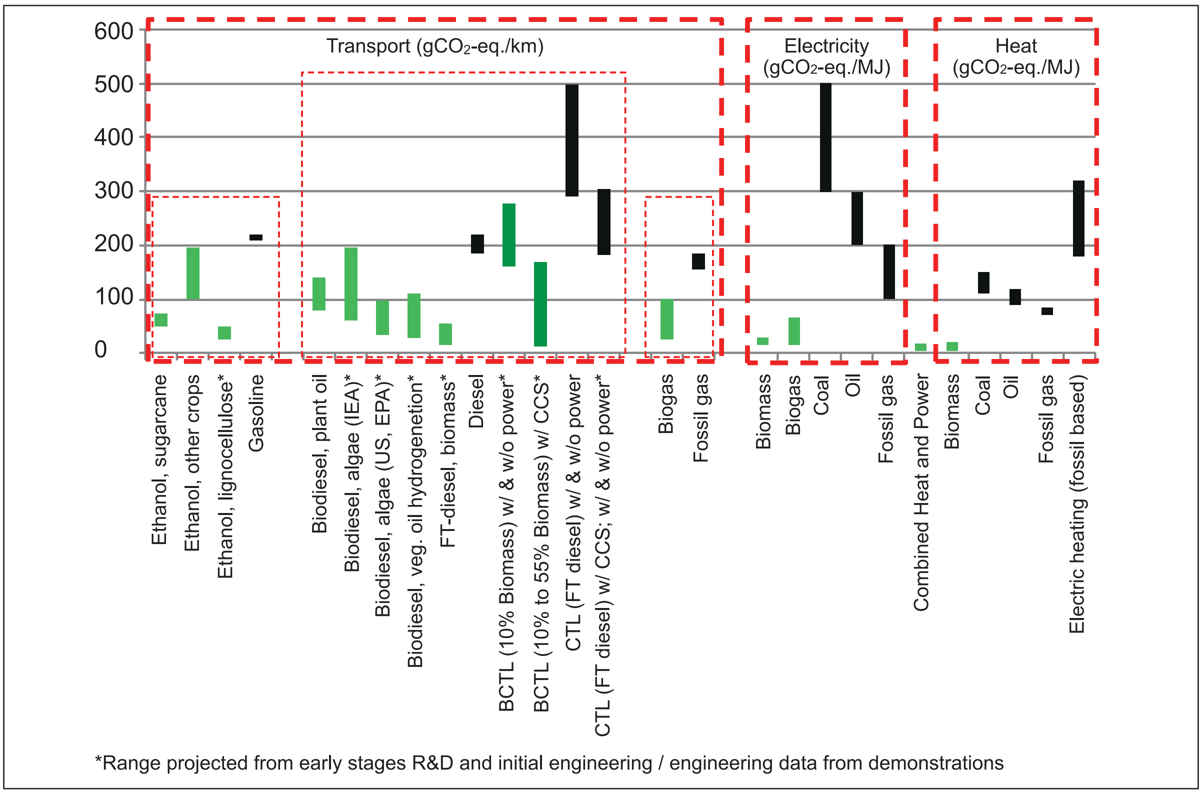


Figure 8. GHG emissions (CO_2-eq.) per unit of output – km transport or MJ electricity/heat delivered to final end use – for a range of bioenergy (green) and fossil (black) options. Ranges reflect variations in performance as reported in literature. Possible LUC emissions are not included here. 'Other crops' refers to corn, sugar beet and wheat; 'biomass' refers to lignocellulosic feedstocks including forest residues, straw and lignocellulosic plants; biodiesel is based on rapeseed, soy and sunflower. 'CTL' and 'BCTL' refer to coal-to-liquid and biomass/coal-to-liquid processes. The BCTL options have darker green bars to indicate that they use both biomass and coal as feedstock; the variation in GHG emissions for BCTL is partly a result of the varying share of biomass in the feedstock mix. For original references see IEA Bioenergy (2011).

from conventional food and feed crops can deliver significant net GHG emissions reduction in situations where LUC emissions are low. Efficient fertiliser strategies (minimising N_2O emissions) and the minimisation of GHG emissions from the conversion of biomass feedstock to solid/liquid/gaseous biofuels are essential.

Process integration and the use of biomass fuels or surplus heat from nearby energy/industrial plants can lead to low net GHG emissions from the feedstock-to-energy carrier conversion process. However, the marginal benefit of shifting to using surplus heat or biomass for the conversion process depends on local economic circumstances and on how this surplus heat and biomass would otherwise have been used. Also, the GHG reduction per unit total biomass used can be small when biomass is used both as feedstock and as fuel to provide the process heat (and possibly electricity) that is required for the conversion of the feedstock to solid/liquid/gaseous biofuels.

It can also be concluded from Figure 8 that solid, liquid, and gaseous biofuels can be produced in ways that lead to significant net GHG emissions but can still generate relatively high GHG savings per unit of biomass or land if they replace very C-intensive fossil options. The use of biofuels for transport can yield very large GHG savings in the future if the alternative is to use transport fuels that are produced from coal in plants that do not employ carbon capture and storage (CCS). This conclusion also holds for transport fuels produced from unconventional oil.

Bioenergy options should be evaluated against several indicators, including biofuel output per unit of land, cost per unit of GHG avoided, and GHG emissions per unit of energy service (the latter measure is shown in Figure 8). A general principle is that inefficient biomass use and high GHG emissions from biomass production and conversion cannot be justified simply because there are even worse fossil alternatives that can be replaced.

Today, substituting biomass for fossil fuels in heat and electricity generation is generally less costly and provides larger emission reductions per unit of biomass than substituting biomass for gasoline or diesel used for transport. However, the stationary bioenergy sector can rely on a range of different low carbon options, while biofuels remain the primary option for decarbonising road transport until all-electric and/or hydrogen fuel cell powered vehicles become widely deployed, which is unlikely to be the case for some decades. Even then it may be difficult for electric systems to compete with liquid fuels for heavy vehicles, long-distance road transport, and sea and air transport.

GHG Emissions Reduction in the Presence of LUC

The quantification of GHG emissions or CO_2 assimilation associated with LUC is subject to many uncertainties. When the amount of C in soils and above-ground biomass is well known for both the pre- and post conversion states it can be straightforward to calculate the GHG effects of dLUC. But in many instances, lack of empirical data on C stocks leads to uncertainties. The effects of some types of dLUC can also be difficult to quantify. One example is when increased forest bioenergy production is associated with changes in forest management practices influencing the forest C stock over time (e.g. higher density planting, changed thinning practices, increased extraction of felling residues and stumps, shortened rotation interval, and use of fertilisers to increase growth).

The inclusion of iLUC in quantifications of LUC effects adds greatly to the uncertainty. Causes of deforestation and other LUCs are manifold making quantification and establishment of causal chains difficult and uncertain. The modelling of such complex phenomena, involving multiple, interlinked and time variable drivers, is a challenge for science. Important aspects include geographical resolution of models, interactions between different parts of the biofuel-food-agriculture system, and how the system responds to changes in market and policy – including instruments to address concerns about deforestation and other LUC. Convergence of results towards substantially more narrow ranges is unlikely in the near future.

Figure 9 shows the results from selected LUC (dLUC+iLUC) quantifications, which focus on LUC associated with so-called 1st generation biofuels that are produced based on conventional food/feed crops. The variations for the same biofuel are illustrative of the complexities and uncertainties inherent in LUC analyses.

The contrasting results for corn ethanol and rapeseed biodiesel reported in one study in Figure 9 illustrate that modelling of links between the biofuel and food systems is crucial. Negative LUC emissions were obtained in this study due to the assumption that biofuel processing by-products would displace imported Brazilian soy as animal feed, which leads to reduced deforestation for soy cultivation in Brazil and thereby avoids deforestation emissions. In the other studies this link between by-product use as animal feed and deforestation in Brazil is less strong. The opposite result has also been reported, i.e. that a shift from soy to corn cultivation in response to increasing ethanol demand in the USA has induced increased soy cultivation in other countries such as Brazil, contributing to increased deforestation.

Finally, when land is converted to produce biomass for energy, future CO_2 assimilation on the land may differ from what would have been the case if the bioenergy plantation had not been established. This is referred to as 'foregone C sequestration' in cases where LUC is estimated to result in reduced CO_2 assimilation capacity. But the future CO_2 assimilation can also be increased, for instance when sparsely vegetated land is forested. The quantification of altered CO_2 assimilation capacity requires that a 'baseline' land use development is defined, which requires model based approaches similar to those used for quantifying iLUC effects.

Despite the significant uncertainties involved in the quantification of LUC emissions it can be concluded that LUC can significantly influence the GHG emissions benefit of bioenergy – in both positive and negative directions. The conversion of forests to croplands for the cultivation of biofuel crops is the most widely discussed example, where the resulting LUC emissions can be so large that it takes several decades – in some instances centuries – before a positive contribution to GHG emissions reduction is achieved. In contrast, if degraded lands are used for bioenergy plantations the GHG reduction can be immediate.

Figure 10 illustrates possible LUC effects by showing how LUC emissions can influence the net GHG reductions obtained by expanding the production of biofuels for transport (see scenario description in the caption). The LUC emissions shown are due to the *additional* need for cultivated land compared to a baseline projection without any crop-based biofuels – thus, it is the sum of dLUC and iLUC emissions that is shown.

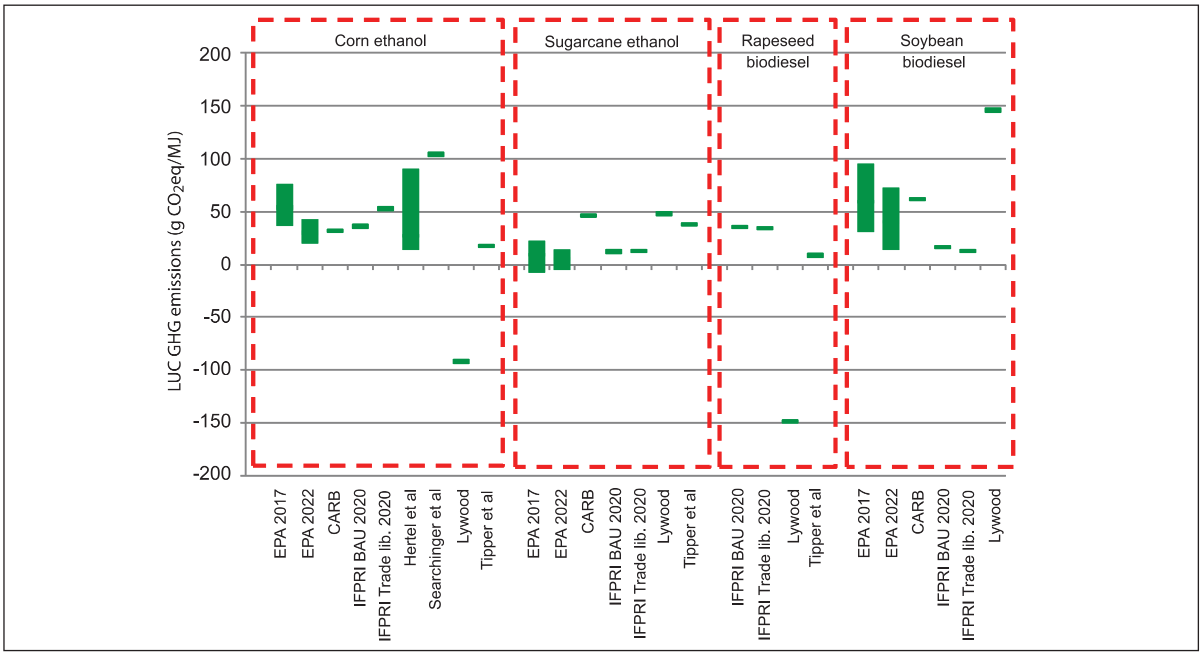


Figure 9. Ranges of model-based quantifications of LUC emissions associated with the expansion of selected biofuel/crop combinations. The studies are reported with LUC emissions amortised over 30 years of production for comparison. For original references see IEA Bioenergy (2011).

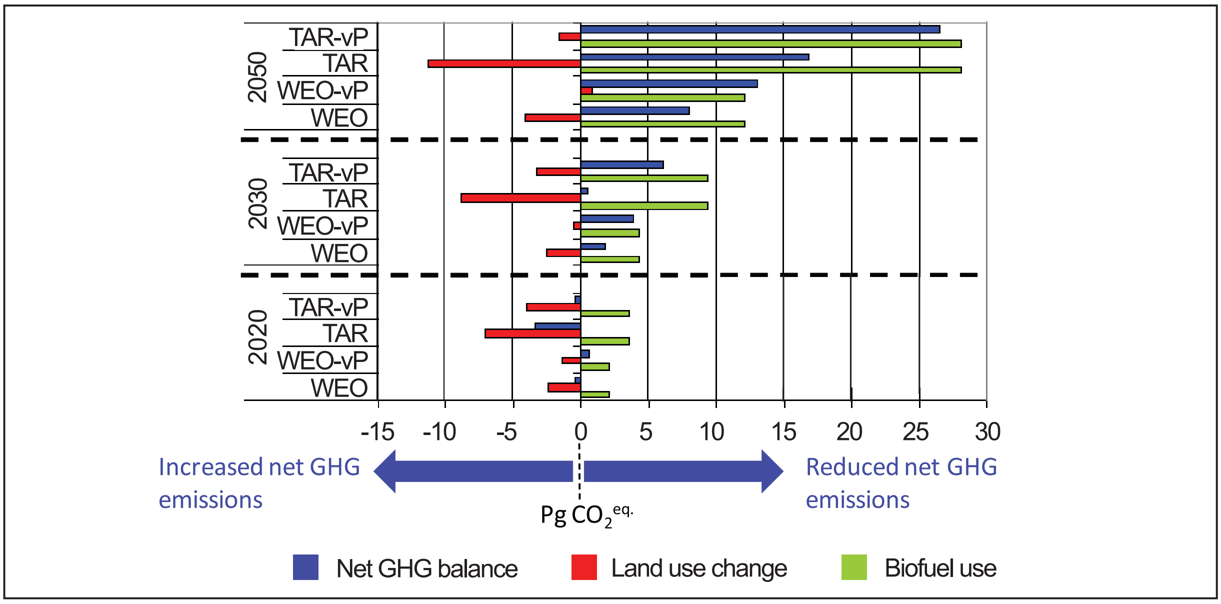


Figure 10. Accumulated net GHG savings of biofuel scenarios. The green 'Biofuel use' bars show GHG savings (positive) from biofuel replacement of gasoline and diesel; the red 'Land use change' bars show GHG emissions (negative) caused by LUC and iLUC; and the blue 'Net GHG balance' bars show the result of subtracting 'Land use change' emissions from 'Biofuel use' savings. WEO has regional biofuel use up to 2030 as projected by the IEA World Energy Outlook 2008 reference scenario (4.2% of total in 2020 and 5.4% in 2030) 2nd generation biofuels are gradually deployed after 2015 (4% of all biofuels in 2020 and 19% in 2030). TAR has roughly twice as high biofuel use and faster deployment of 2nd generation biofuels (33% of all biofuels in 2020 and 51% in 2030). The vP scenarios have higher agricultural productivity growth in developing countries leading to lower LUC. Source: Elobio, 2010.

The additional cultivated land is commonly converted from existing pastures or natural grass and forest land, habitats that contain higher C stocks compared to the cultivated land which thus results in significant LUC emissions.

The TAR scenario in Figure 10 assumes expansion of biofuel production in accordance with mandatory, voluntary, or indicative targets announced by major developed and developing countries. It generates higher climate change mitigation benefit than the IEA/WEO 2008 reference scenario (IEA 2008) due to a higher share of biofuels in the total transport fuel mix and also due to faster development for so-called 2nd generation biofuels using lignocellulosic feedstocks and avoiding deforestation, thus leading to lower LUC emissions and higher GHG savings from the fossil fuel substitution.

The vP scenarios illustrate how the pace of agricultural productivity growth influences the GHG savings potential of biofuel expansion strategies. Lower arable land requirements due to assumed faster agricultural productivity increases in non-industrialised countries (+10-20% by 2050) result in less LUC in these scenarios, and consequently in higher net GHG reductions.

In Figure 10, the negative impact of LUC emissions is greatest in the near term and the relative importance of LUC emissions for the cumulative net GHG savings decreases over time. Therefore, one commonly used argument for promoting biofuels for transport – that it is one of few near term options for climate change mitigation in the transport sector – may not hold unless the cumulative net GHG savings can grow faster than in the illustrative cases shown in Figure 10. However, the strict requirement for almost immediate net GHG savings, implying practically zero LUC emissions, can be questioned (this aspect is discussed in more detail below). Also, although the graph may indicate that the GHG balance is usually positive only in the long-term, this may not be true for every biofuel. Some alternatives, such as sugarcane ethanol, are able to achieve a significant positive balance in the short-term. This is also the case when solid biofuels are used for heat and power.

Climatic Consequences of Other Changes Associated with LUC

Besides influencing the atmospheric concentration of GHGs, bioenergy and associated LUC influences climate through:

- particulate and black carbon emissions from small-scale bioenergy use;
- aerosol emissions associated with forests; and
- modifying physical properties of the surface, altering for instance evapotranspiration and albedo.

If the land becomes darker (i.e. albedo is reduced) more solar energy is absorbed leading to increased warming. Conversely, if the land becomes lighter (i.e. more reflective – albedo is increased) there is cooling.

The albedo of a forested landscape is generally lower than that of cultivated land, especially in areas with snow, but also under snow-free conditions. Studies indicate that deforestation at mid and high latitudes induces cooling due to an increase in albedo; the increased area of non-forest vegetation having higher albedo leads to less solar energy being absorbed and this outweighs the warming effect of GHG emissions from the deforestation. But in tropical areas deforestation reduces evapotranspiration more than in other areas and the resulting loss of evaporative cooling may compensate for the albedo increase, so that LUC can lead to local warming.

Thus, under specific circumstances afforestation measures may not automatically contribute to mitigation of global warming because the cooling effect of most of the carbon sequestered is counteracted by the warming effect of albedo changes. Incorporation of albedo effects in analyses of the climate change mitigation benefit of bioenergy systems also indicates that both in regions with seasonal snow cover or a seasonal dry period (e.g. savannas) the influence of albedo changes can be large and counteract the benefit of bioenergy. Conversely, albedo increases associated with the conversion of forests to bioenergy crops may counteract the warming effect of CO_2 emissions from the deforestation.

OPTIONS FOR MITIGATING LUC ASSOCIATED WITH BIOENERGY

Integrated Land Use and Increased Land Use Efficiency in Agriculture

Reduction in land requirements for food and bioenergy production would lead to less LUC pressure and consequently improved GHG balances for expanding bioenergy systems. There are still substantial yield gaps to exploit and large opportunities for yield growth in food crop production – not the least in many developing countries. There is also scope for sizeable improvements in land use efficiency for livestock production and dietary changes towards less land-demanding food. For example, shifts from ruminant meat to pig and poultry consumption and increased vegetable consumption can reduce land requirements for food production substantially (Wirsenius *et al.* 2010).

In the long-term, bioenergy feedstock could be produced on agricultural land no longer required for food production, in an optimistic scenario where the productivity improvements in agriculture are high enough to outpace food demand. LUC emissions from bioenergy expansion can then be substantially lower as less natural land needs to be converted to cultivated or grazed land. There is also a large potential growth in yield from dedicated bioenergy plants that have not been subject to the same breeding efforts as the major food crops. This would further reduce the LUC pressure associated with food and bioenergy development.

Strategies aiming at increased land use efficiency need to consider that high crop yields depending on large inputs of nutrients, fresh water, and pesticides can contribute to negative ecosystem effects. Such negative tradeoffs might be controlled through standards, certification systems, or regulatory requirements, but this may not be effective in regions with less stringent environmental regulation and/or limited law enforcement capacity.

Even so, a significant potential for improving the currently low productivity of rain-fed agriculture exists in many regions of the world through improved soil, water and nutrient conservation, fertiliser use and crop selection that can increase land use efficiency while avoiding or mitigating negative ecosystem effects. Available best practices are not at present applied in many world regions due to a lack of dissemination of knowledge, capacity building, availability of resources and access to markets. Conservation agriculture and mixed production systems (double-cropping, crop with livestock, and/or crop with forestry) have the potential to improve land and water productivity as well as carbon sequestation, and to improve the food security and resource use effciency. Bioenergy feedstocks may be one output from such integrated systems and the integration can also take place at the feedstock conversion level where by-products can replace cultivated animal feed such as soy and corn and also reduce grazing requirements.

Use of 'Low LUC Feedstocks'

One promising way to reduce emissions from LUC is to increase the amount of lignocellulosic feedstock grown on low-carbon pasture land less suitable for annual crops, thereby decreasing the pressure on prime cropping land. Naturally, LUC effects are lower if feedstocks not requiring dedicated land for their production are used. As noted earlier, post-consumer organic waste and by-products from the agricultural and forest industry represent a large biomass resource base and their utilisation as feedstock for bioenergy can avoid LUC if these biomass sources have no alternative use.

The use of some types of organic waste can also reduce the negative effects associated with how they otherwise are managed. For instance, anaerobic digestion of suitable organic waste to produce biogas can reduce local waste problems and contribute to recirculation of nutrients back to agriculture. If disposed of in landfills, organic wastes may also cause methane emissions as they decompose, leading to a greater climate impact than if they are burned directly, although over a different time profile.

If not utilised for bioenergy some of these biomass sources (e.g. harvesting residues left in the forest) would retain organic carbon out of the atmosphere for a longer time than if used for bioenergy. This delay in release of carbon can be considered a benefit of the conventional system in evaluations using only a short time horizon and also a relevant factor in longer term accounting and regions where biomass degradation is slow (e.g. boreal forest).

Figure 11. Integration of *Eucalyptus* with cattle production in Brazil. Combined bioenergy-food production systems may become more common in the future as a way to diversify and optimise the productive use of land, water and other resources. Courtesy: Laércio Couto, RENABIO.

Land Use Restrictions

Society can avoid high levels of LUC emissions by stipulating that bioenergy cannot be produced based on feedstocks obtained from lands earlier covered by high C stock forests or peatlands that cause very large CO_2 emissions when converted to bioenergy feedstock production.

Society can also stimulate the use of specific land types where establishment would lead to low LUC emissions and where the iLUC risk is low, i.e. land with little alternative use. In this context, the use of marginal abandoned farmland and unused degraded lands has been proposed as a promising option that might also contribute to restoration of degraded soils and habitats. For instance, Brazil has recently promoted some land use restrictions for bioenergy feedstock production through agro-ecological zoning that defines the acceptable areas for production expansion of sugarcane (in 2009) and oil palm (in 2010).

However, there are several shortcomings and challenges to address:

- Although land use restrictions applied only to biofuels feedstock cultivation could decrease indirect impacts on LUC, land use restrictions can more effectively avoid the indirect effects of bioenergy expansion if they become internationally recognised and applied to all types of biomass use, including the production of food, biobased chemicals, paper and other wood products, etc.
- The strict exclusion of specific land types as a global criterion may not harmonise well with local development objectives where conversion of a certain proportion of such lands has been assessed as defendable from the perspective of biodiversity and other resource conservation criteria.
- Marginal farmlands and degraded lands can be important for the subsistence of rural populations (e.g. used for animal grazing) who might move to new areas if displaced by bioenergy plantations, so causing iLUC. Even though those impacts are not comparable to those caused by iLUC in non-degraded areas, this issue should be addressed. Also, marginal lands may hold high biodiversity values and establishment of bioenergy plantations may reduce down stream water availability in water scarce areas.
- Lastly, the establishment of bioenergy plantations on these land types may require large agronomic and other inputs, which increases the cost of the biomass production and increases the GHG emissions from biomass production.

As discussed in the next section, the strict exclusion of land types where it is expected that conversion will lead to CO_2 emissions can be questioned because converting such lands for bioenergy use may eventually result in net GHG savings, with time lags depending on both land use change emissions and the GHG savings achieved from the fossil fuel substitution. A total exclusion implies that a relatively short-term perspective is used.

BIOENERGY AND LUC IN THE CONTEXT OF GLOBAL CLIMATE TARGETS

The question of how LUC emissions can influence the climate change mitigation benefit of specific bioenergy projects, or national or regional bioenergy targets, needs to be complemented with a view on bioenergy and LUC in the context of global GHG emissions and climate targets.

The Relative Importance of LUC Emissions and Fossil Fuel Emissions

Figure 12 shows changes in atmospheric CO_2 concentration as a result of three different scenarios up to 2100. The upper blue trend line corresponds to a business-as-usual (BAU) scenario where the atmospheric CO_2 concentration reaches about 850 ppm in 2100, i.e. more than triple pre-industrial CO_2 concentration levels. The LUC (deforestation) emissions in this BAU scenario are assumed to decrease dramatically to become about one-tenth of year 2010 emissions by 2100. Thus, fossil fuel emissions, being already more than five times current LUC emissions, completely dominate.

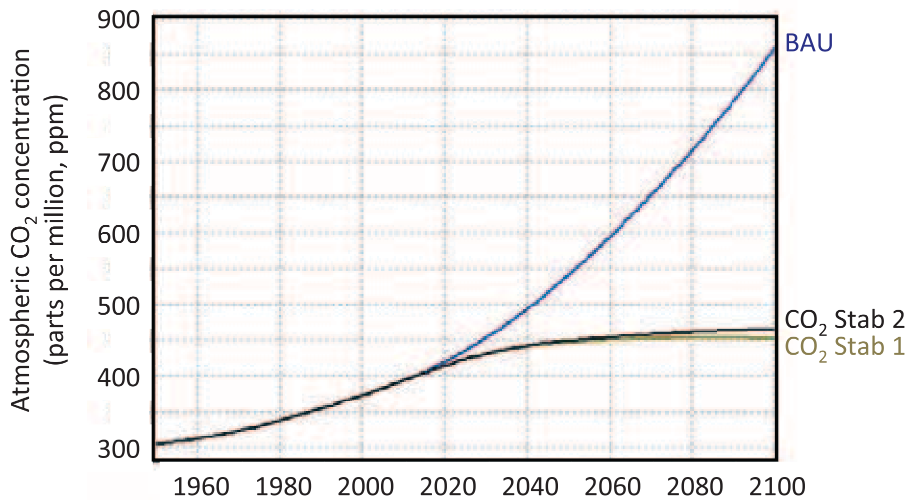


Figure 12. Changes in atmospheric CO_2 concentration associated with three different GHG emission pathways, as described in the text. The diagram is produced using the Chalmers Climate Calculator, available at *www.chalmers.se/ee/ccc*

The two lower trend lines correspond to CO_2 Stabilisation (CO_2-Stab) Scenarios where atmospheric CO_2 concentration levels stabilise during this century. The likelihood that the global average surface warming stays below 2°C for these two scenarios depends on the climate sensitivity and on emission rates for other GHGs than CO_2. In the CO_2-Stab 1 scenario deforestation is reduced as in the BAU scenario, while it stays constant at the 2010 level throughout the century in CO_2-Stab 2.

The big difference between the upper BAU trend line and the lowest CO_2-Stab 1 trend line is due to the differences in fossil fuel emissions. Meanwhile, the large differences in deforestation rates and associated LUC emissions only cause the small difference between the two lower lines. This shows the dominant impact of fossil fuel emissions and the relatively low impact of land use change.

One can assign many different qualitative interpretations to the trend lines in Figure 12, related to energy conservation and efficiency improvements, to implementation of renewables, nuclear, carbon capture and storage, and other technologies – and also related to drivers and policies affecting deforestation and other LUC. Some observations can however be made from Figure 12 that are valid for the full range of such studies:

- Stabilisation of atmospheric CO_2 concentrations at levels proposed in relation to the 2ºC target requires drastic changes in the way the global energy system functions.
- The effect of strongly reduced LUC emissions is relatively small compared to what is required for reaching such stabilisation targets, but the lower the target the more important it is to reduce LUC emissions.

Implications for the Role of Bioenergy in Climate Change Mitigation

Climate targets set limits on future GHG emissions. In order to stabilise the concentration of GHGs in the atmosphere, emissions need to peak and decline thereafter. Many different emission trajectories are compatible with a given stabilisation target. Mitigation efforts over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels. The ceiling on GHG that can be released over the coming decades, in order to minimise the risk of a temperature rise greater than 2°C, can be calculated as illustrated in Figure 13, which considers CO_2 emissions up to 2050. The concept 'emissions space' focuses on global cumulative emissions up to a given year and gives a complementary perspective to that provided by emission trajectories. For CO_2, the concept of emissions space is relevant in relation to temperature targets since the peak warming appears to be insensitive to the CO_2 emissions pathway, i.e., timing of emissions or peak emission rate.

One critical strategic question is how society should make use of the remaining allowable 'space' for GHG in the atmosphere. At present, fossil energy infrastructure is expanding rapidly around the world, and given the typical lifetime of many decades for fossil energy plants this implies considerable claims for future GHG emission space. Likewise, the establishment of new energy technologies and associated infrastructure would in itself occupy part of the remaining space for GHG emissions. For example, electric vehicle fleets will contribute to increasing atmospheric CO_2 levels as long as electricity is mainly generated from fossil fuels (although, they may cause lower GHG emissions than present gasoline and diesel vehicles). Yet, promotion of electric vehicles can be justified because they can provide efficient transport services that cause low GHG emissions in a future situation when electricity is less reliant on fossil fuels.

Similarly, in view of the long-term benefit of bioenergy, it may be acceptable to use part of the GHG 'space' for developing a bioenergy industry capable of providing renewable and climate friendly energy services for the world in the long-term. Furthermore, the GHG emissions associated with bioenergy will decrease over time as above-ground biomass and soil C stabilise at new equilibrium levels, conversion technologies improve and use renewable process fuel, and feedstock production systems develop into less GHG intensive systems. Should CCS technologies become available, bioenergy is currently the only energy technology that, combined with CCS, allows net removal of CO_2 from the atmosphere, making it pivotal for achieving ambitious climate protection targets should the peak in GHG emissions occur late. Thus, unfavourable near term climate performance due to LUC emissions does not disqualify bioenergy from being part of a long-term solution to the climate problem. However, the need to manage other impacts of LUC, such as on biodiversity, water and soil conservation, should not be forgotten.

CONCLUSIONS FOR POLICY AND FOR STAKEHOLDERS INVOLVED WITH BIOENERGY DEVELOPMENT

It has been shown above that LUC can significantly influence the climate benefit of bioenergy. The use of waste and agricultural/forestry residues as feedstock is one way to reduce the incidence of LUC emissions. Careful expansion of suitable biomass plantations – via integration with food and fibre production, avoiding displacement, or targeting unused marginal and degraded lands – can mitigate LUC emissions associated with bioenergy expansion and in some instances lead to sequestration of atmospheric CO_2 in soils and above-ground biomass, enhancing the climate benefit.

A move to lignocellulosic feedstocks for bioenergy will be one promising way to reduce emissions from LUC since this can decrease the pressure on prime cropland. As the production of lignocellulosic feedstocks commonly requires less fuel, fertiliser and other inputs there is also scope for higher GHG savings than when biofuels are produced from conventional crops such as cereals and sugar beet. However, if bioenergy is to provide energy for both transport and for heat and electricity production, a mix of lignocellulosic material and conventional food/feed crops is likely to be used as bioenergy feedstock during the coming decades. Strategies to increase agricultural productivity, especially in developing countries, will be critical to minimising LUC emissions. In general, stimulation of increased productivity in all forms of land use reduces the LUC pressure.

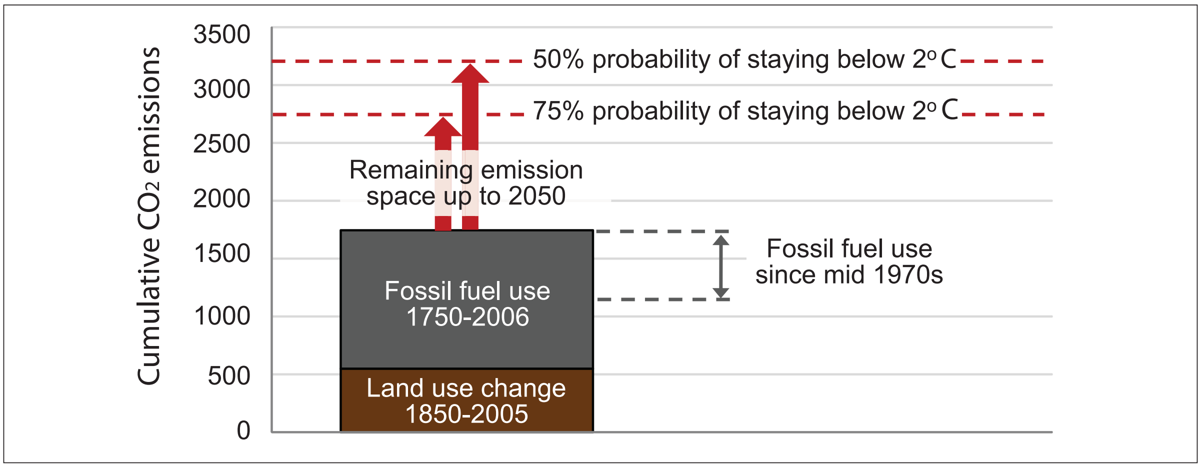


Figure 13. Cumulative CO_2 emissions and indicative remaining emission space in relation to a 2°C target based on Meinshausen *et al*, 2009.

Measures to reduce LUC should be based on a holistic perspective, recognising that the climate benefit is just one of many rationales for ecosystem protection. Strict focus on the climate benefits of ecosystem preservation may put undue pressure on valuable ecosystems that have a relatively low C density. Measures also need to acknowledge that the conversion of some natural ecosystems into high-yielding plantations could provide an effective response to climate change concerns, despite leading to some near-term LUC emissions.

Future LUC rates will depend on the willingness of national governments to protect forests and other natural ecosystems – and the effectiveness of legislation and other measures to reduce deforestation. But they will also depend on whether sustainable land use practices become established in regions where agriculture continues to expand into new areas. In some places removal of natural vegetation to establish agriculture leads only to short-term benefits, which are followed by land degradation and low productivity, in turn leading to the need for further land conversion. The application of established best practice and mixed production systems can sustainably increase land productivity. These measures are not applied in many developing countries at present because of a lack of information dissemination, capacity building, availability of resources, and access to capital and markets. Economic pressure to maximise short-term returns may also make landholders in industrialised countries reluctant to apply sustainable techniques that would result in a short-term yield penalty.

Policies that stimulate biofuel production influence global agricultural markets and need to become part of the policy framework that supports agricultural development in the world regions that are likely to be affected most by increased biofuel demand. Sensible land development programmes can have better prospects for achieving sustainable development than the top-down establishment of global sustainability criteria using strong and inflexible measures.

Some policy options for addressing bioenergy driven LUC can be proposed as follows:

- Promote only bioenergy options that meet set requirements with respect to LUC, e.g. use only bioenergy which is certified to have avoided certain types of LUC or to have met target GHG reduction thresholds. Identification of such certifiable biomass sources will be difficult given the complexity and interconnectedness of the agricultural and forestry systems.
- Assign a certain level of LUC emissions to bioenergy options, based on their land use replacement and quantification of associated LUC emissions using best available harmonised data and methodology. Given the uncertainty of such quantifications, it might be advisable to allow producers that are close to the threshold to buy emission rights as a way to comply with eligibility requirements rather than to exclude them from the market.
- Support development of bioenergy options that have smaller LUC risks, such as biomass production on degraded or other unused lands, integrated biomass/food/feed production, and the use of residues and waste, or lignocellulosic plants that can avoid competition for prime cropland. Such options might receive an extra premium in the initial phases to help them become established. Importing countries may also consider the possibility to include specific requirements (e.g. via preferential agreements, legislation and/or certification systems) and thereby provide a niche market for such alternative bioenergy options. These can in turn influence the development of conventional bioenergy production by providing attractive examples and also opportunities for learning about alternative production.
- Shape GHG accounting policies to encourage low-LUC bioenergy. For example, carbon neutral status could be applied only to bioenergy produced and consumed in countries that include LUC and forest management emissions/removals in GHG accounting.
- Promote an integrated and international approach among energy, agriculture and development polices to stimulate the much-needed agricultural productivity increases in the developing world. Including land use efficiency as a metric should not lead to a one-dimensional incentive for productivity increases. The art will be to combine relatively high yields with environmentally sound management systems.

It should be noted that the above options for addressing bioenergy-driven LUC may not, depending on their implementation, be able to completely avoid indirect GHG emissions, due to the interconnectedness of the agricultural and forestry systems. Over the longer term, a global C cap that regulates both fossil and biospheric C emissions could be developed as a flexible policy option. Under such a system, countries could decide to use a certain share of their allowed emission space for developing a bioenergy industry to secure long-term domestic energy supply, or to generate export revenues. These countries would then need to reduce C emissions from other activities, or buy emission rights.

Policy makers will certainly promote climate friendly alternatives in addition to bioenergy. The development of such alternatives may be a particular challenge in the transport sector where options such as hydrogen and electric vehicles relying on hydro, wind, and solar PV will require decades to become established on a substantial scale. Consequently, unless biofuels contribute to emissions reduction in the transport sectors, policy makers will have to target increased vehicle efficiency and structural changes in transport and other societal systems as major options for emissions reduction in the next one to two decades. Furthermore, meeting ambitious climate targets will also require climate friendly fuels in air and marine transport where no alternative to biofuels is currently available. As another option, reduction targets for the stationary energy system could be increased, leaving more emission space for the transport sector.

Increasing bioenergy production and use contributes to establishing bioenergy as a global option and incentivises an increased global infrastructure to produce, handle, and consume biomass-based fuels. In such a scenario there is a risk that bioenergy may be demanded despite negative environmental impacts, simply because the energy is needed and people are used to biomass-based fuels. Similarly, concerns about negative socio-economic effects may become downplayed due to a common perception that large-scale bioenergy is simply necessary for maintaining lifestyles. These considerations lead to the conclusion that the current development of sustainability frameworks to guide bioenergy development is warranted.

The overall conclusion in this report is that emissions from LUC can be significant in some circumstances, but short-term emissions from LUC are not sufficient reason to exclude bioenergy from the list of worthwhile technologies for climate change mitigation. Policy measures implemented to minimise negative impacts of LUC should be based on a holistic perspective recognising bioenergy's strong interconnectedness with food and fibre, and the multiple drivers and impacts of LUC. Bioenergy development ultimately depends on the priority of bioenergy products versus other products obtained from land – notably food and conventional forest products – and on how much biomass can be mobilised in total from agriculture and forestry. This in turn depends on natural factors (e.g. climate, soils, and topography) and on agronomic and forestry practices employed to produce the biomass, as well as how society understands and prioritises nature conservation and soil/water/biodiversity protection and how the production systems are shaped to reflect these priorities.

LIST OF RECOMMENDED READING

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ONLINE MODELS

Two online models have been developed at Chalmers University of Technology. *GETOnline* is an interactive web-based global energy systems model. It can be used to explore policy and technology options in a climate perspective. An atmospheric CO_2 model calculates the resulting CO_2 concentration based on the emissions from the energy system. The model can be found at *www.chalmers.se/ee/getonline.* The *Chalmers Climate Calculator* is a web-based climate model that mimics results from advanced climate models. Two different modes are available: a global aggregate version and a version where the world is divided in two regions. The model can be found at *www.chalmers.se/ee/ccc.*

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IEA Bioenergy

IEA Bioenergy is an international collaboration set up in 1978 by the IEA to improve international co-operation and information exchange between national RD&D bioenergy programmes. IEA Bioenergy's vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis, thus providing increased security of supply whilst reducing greenhouse gas emissions from energy use. Currently IEA Bioenergy has 22 Members and is operating on the basis of 13 Tasks covering all aspects of the bioenergy chain, from resource to the supply of energy services to the consumer.

Further Information

IEA Bioenergy Website
www.ieabioenergy.com

IEA Bioenergy Secretariat
John Tustin – Secretary
PO Box 6256
Whakarewarewa
Rotorua
NEW ZEALAND
Phone: +64 7 3482563
Fax: +64 7 348 7503
Email: jrtustin@xtra.co.nz

Arthur Wellinger – Technical Coordinator
Nova Energie GmbH
Châtelstrasse 21
Aadorf, CH-8355
SWITZERLAND
Phone: +41 52 365 4310
Fax: +41 52 365 4320
Email: arthur.wellinger@novaenergie.ch

iea Energy Technology Network

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