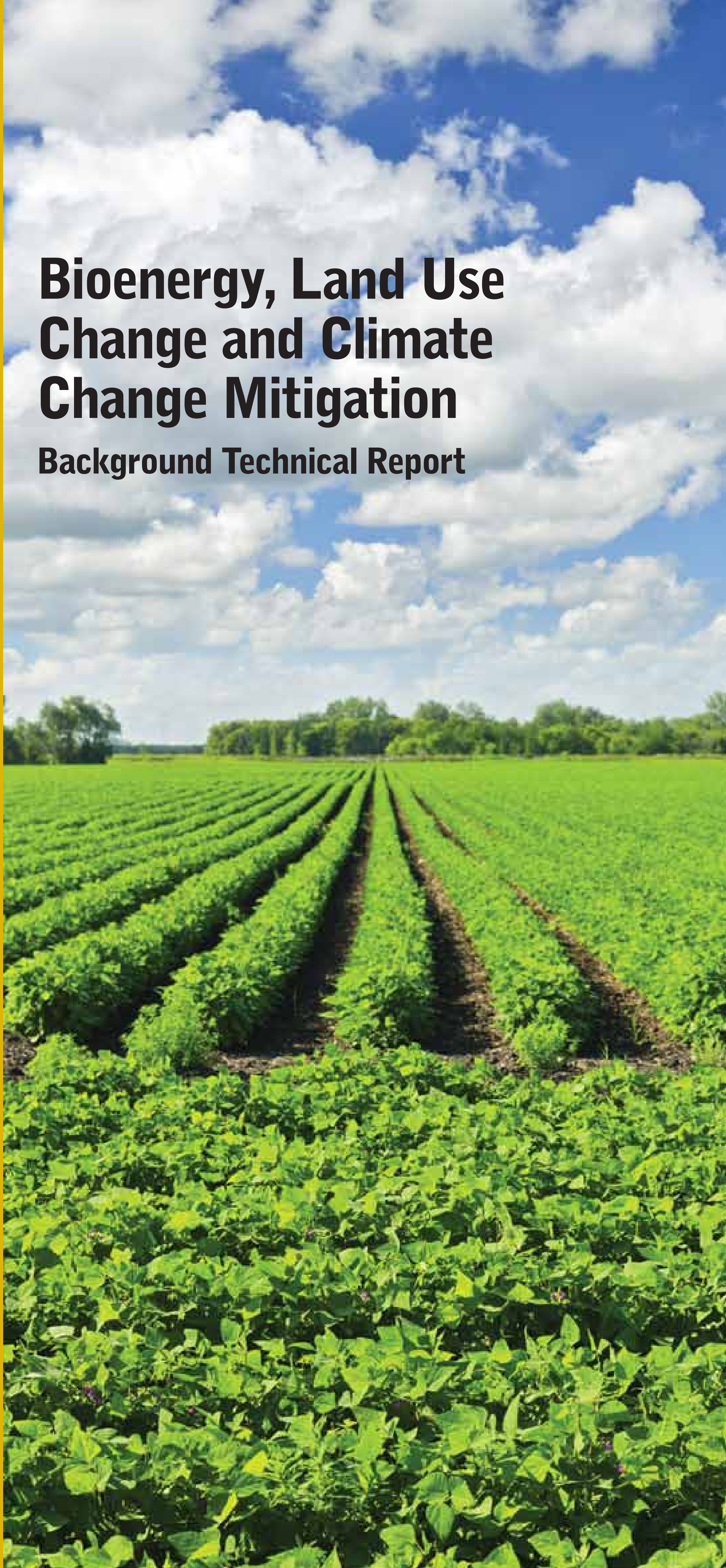
Bioenergy, Land Use Change and Climate Change Mitigation

Background Technical Report



This report was prepared by Associate Professor Göran Berndes, of Chalmers University of Technology, Sweden; with input from contributing authors Mr 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 this background report is to supply a more detailed, fully referenced version for practitioners, and researchers, in support of the short version (IEA Bioenergy:ExCo:2010:03) which was aimed at policy advisors and policy makers.

IEA Bioenergy

IEA Bioenergy:ExCo:2011:04

BIOENERGY, LAND USE CHANGE AND CLIMATE CHANGE MITIGATION

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Background Technical Report

KEY MESSAGES

The sustainable use of bioenergy presents a major opportunity to address climate change by reducing fossil carbon dioxide 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 2°C (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.

***Cover Picture:** Soybean crop.*

TABLE OF CONTENTS

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The major opportunities to reduce fossil carbon dioxide (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* 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 2ºC (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 (C) 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 nitrous oxide (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.

* ***IEA Bioenergy**, 2009. Bioenergy – a sustainable and reliable energy source: a review of status and prospects. IEA Bioenergy: ExCo: 2009:06; and **IEA RETD and IEA Bioenergy**, 2010. BUBE: Better use of biomass for energy. Background report to the position paper of IEA RETD and IEA Bioenergy.*

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 agricultural 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. savannahs), 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 (CH_4) 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 socio-economic 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. Landowners 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 (GHG) emissions arising from LUC.

Bioenergy is different from the other renewable energy technologies in that it is a part of the terrestrial carbon (C) cycle. The carbon dioxide (CO_2) emitted due to bioenergy use was previously sequestered from the atmosphere and will be sequestered again if the bioenergy system is managed sustainably, even though emissions and sequestration are not necessarily in temporal balance with each other (e.g. due to long rotation periods of forest stands). Bioenergy use may also cause changes in terrestrial C stocks such as when a forest is converted to cropland for biofuel feedstock production.

Both biofuels for transport and biomass use for heat and power are considered in this report. 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 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 fuels (or other energy sources) and of 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[#].

The report describes options for mitigating bioenergy-induced LUC and the associated GHG emissions, and proposes ways for policy makers to address the LUC concerns. Perspectives on LUC emissions are presented considering both short-term GHG targets and longer-term temperature targets.

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.

[#] *See list of recommended reading at the end of this report.*

THE CARBON CYCLE

The Principal Carbon Pools and Fluxes

Understanding the global carbon cycle and how it is affected by anthropogenic activities is important for developing a view on the climate change mitigation benefits of bioenergy strategies.

Figure 1 shows the principal C pools and the fluxes between them. 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.

This report refers to the biosphere as consisting of the terrestrial biotic pool and the soil organic carbon (SOC) component of the pedologic pool. The SOC pool consists of humus and charcoal C, including plant and animal residues at various stages of decomposition; substances synthesised from the decomposition products; and the living micro-organisms and small animals with their decomposing products. The aquatic biomass (plankton, algae, etc.) is also part of the biotic pool, but since this report concerns terrestrial ecosystems only, 'biotic pool', 'biosphere', etc. is used to designate only the terrestrial part of the total biotic pool and SOC. The biospheric C losses arising from LUC will consequently be the sum of terrestrial above ground biotic C losses and SOC losses.

The above ground terrestrial part of the biotic pool is relatively small – containing about three times less C than what is stored as SOC in the soil pool and about seven times less than the fossil C pool. However, the C exchange rate between the biosphere and the atmosphere is relatively high - about 120 Pg of atmospheric C is fixed in photosynthesis each year. This is roughly balanced by plant and soil respiration that transfers back similar amounts of C to the atmosphere. These C flows between the biosphere and the atmosphere vary from year to year. The C exchange time scales can vary up to several years due to (i) the annual cycle in global CO_2 caused mainly by spring vegetation growth in the Northern Hemisphere, and (ii) inter-annual variability associated mainly with the El Niño-Southern Oscillation (ENSO) climate signal and with volcanic activity[1].

As illustrated in Figure 1, the biosphere and the atmosphere can be described as one C pool – here designated the atmosphere-biosphere system – that is characterised by large bi-directional C flows between the two pools that are difficult to quantify and to control[3]. 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 better quantified. However, errors in the quantification of fossil fuel emissions require increasing attention in major regions undergoing rapid economic growth, where errors of as much as 20% have been detected[4].

Figure 2 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.

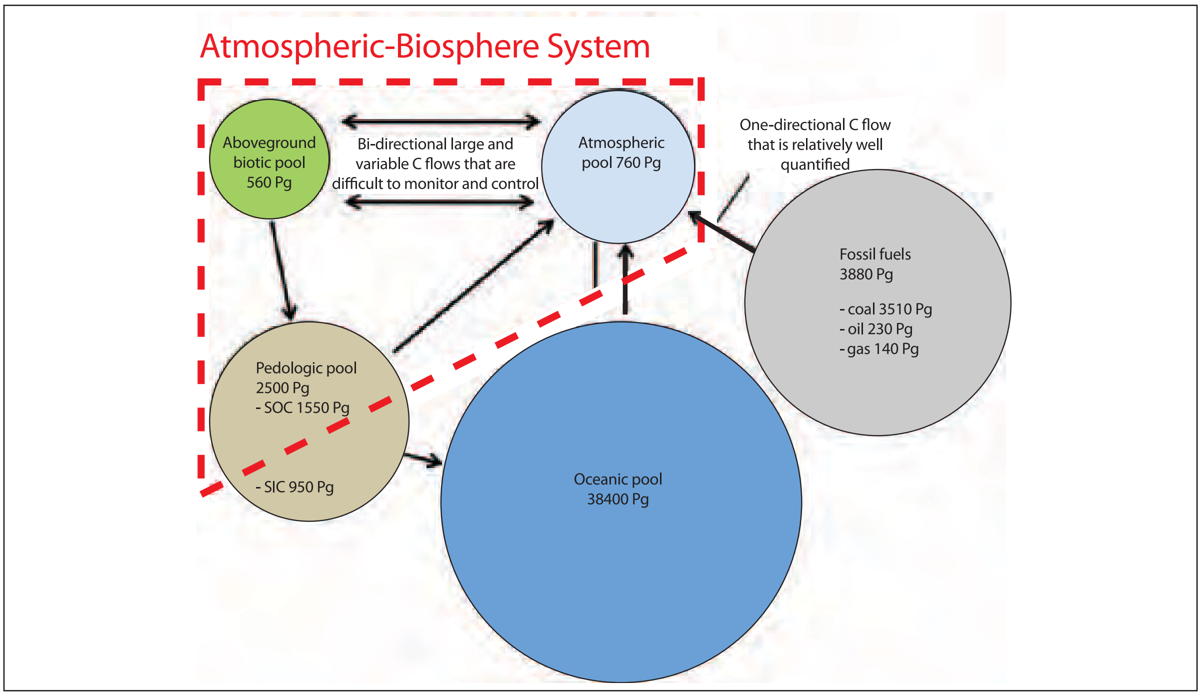


Figure 1. *The five principal C pools and fluxes between them. The biosphere and the atmosphere together make up the atmosphere-biosphere system, which is characterised by large bi-directional flows that are highly variable from year to year, difficult to quantify, and expected to be influenced by climate 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*[2].

Carbon emissions due to fossil fuel use represent the largest source and at present are more than five times larger than the LUC emissions. Thus, while the fossil C flow to the atmosphere is an order of magnitude smaller than the bi-directional C flows between the biosphere and the atmosphere, it is much larger than the net flow of C from the biosphere to the atmosphere, which is caused by land use and LUC.

About 330 Pg of fossil C has been emitted to the atmosphere (or to the atmosphere-biosphere system) since 1750, with two-thirds of these fossil C emissions taking place since 1970[5]. A few percent of anthropogenic C emissions to the atmosphere comes from cement production[6].

Climate change is expected to influence vegetation distribution and the C exchanges between the biosphere and the atmosphere in ways not yet well understood. Processes that destabilise organic matter in response to disturbances such as warming or land use change are poorly understood and the longer-term influence of increased atmospheric

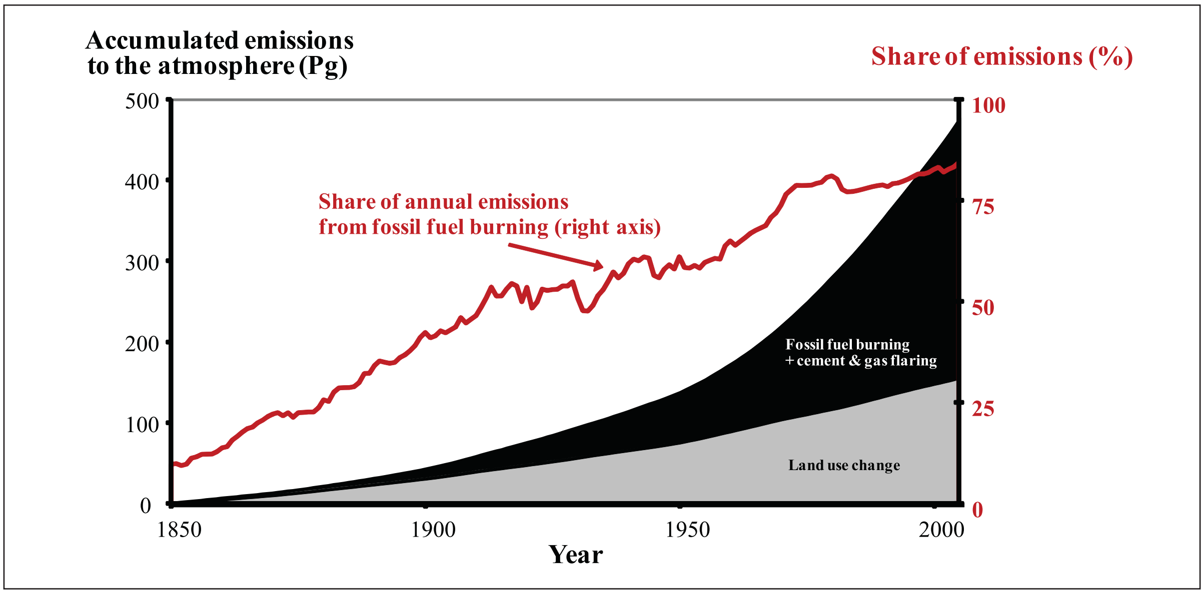


Figure 2. *Accumulated anthropogenic C emissions to the atmosphere since 1850. The contribution from cement manufacturing and gas flaring is 1-2% of the total accumulated emissions. Data source: The Carbon Dioxide Information Analysis Center (CDIAC) of the US Department of Energy (DOE).*

C levels on biospheric C levels is uncertain. To acquire the data necessary for a good understanding of C dynamics in ecosystems, and how this is affected by human actions, requires the development and integration of monitoring programmes[7].

The CO_2 fertilisation effect – elevated CO_2 levels in the ambient air stimulating plant growth[§] – results in a portion of the C emissions being transferred from the atmosphere to the biosphere[8]. Part of the C that is emitted to the atmosphere is also assimilated in the biosphere due to reforestation in some parts of the world. Forests in Europe and North America, for example, presently function as a C sink[9]. Quantifications of the effects of reforestation and CO_2 fertilisation are uncertain, but estimates indicate that the biotic pool as a whole is presently a net sink of C – despite the biospheric C losses associated with land use and LUC – and that the CO_2 fertilisation effect is one major contributing factor. One study estimated that during 2000-2006, the terrestrial biosphere sequestered C corresponding to roughly one-third of the total C emissions to the atmosphere[10].

Climate-carbon cycle models indicate that the CO_2 fertilisation effect might become weaker in the future and that the terrestrial biosphere may even become a C source in the final decades of the 21st century if atmospheric CO_2 levels increase radically, but projections are uncertain[11]. For example, the Amazon rainforest, which is the world's most extensive rainforest holding large volumes of C, is judged to be increasing its net C sequestration at present as a result of CO_2 fertilisation effects, but may eventually switch from C sink to C source. The forest loses C due to deforestation, fragmentation and degradation, and research also indicates that the Amazon is sensitive to drought that can cause massive C loss mainly through the death of trees[12]. Climate-induced drying of the Amazon might accelerate climate change through carbon losses and changed surface energy balances. However, studies report varying results and in contrast other studies report that the Amazon forests appear vulnerable to increasing moisture stress – with the potential for large carbon losses to exert feedback on climate change – and also that the Amazon shows unexpected resiliency during drought[13].

There are other naturally occurring processes that remove C from the atmosphere-biosphere system, such as geochemical weathering and in particular the uptake of atmospheric CO_2 by the ocean, which has taken up approximately 40% of anthropogenic-sourced CO_2 from the atmosphere since the beginning of the industrial revolution[14] (Figure 1). However, the long time scales characterising these processes make them insufficient in terms of balancing the effects of human activities influencing different C pools[15].

Options for Relocating Carbon Within the Atmosphere-Biosphere System

Besides the CO_2 fertilisation effect leading to the transfer of C from the atmosphere to the biosphere, society can also employ different approaches to actively relocate C from the atmosphere to the biosphere. There are several options for storing biospheric C in more stable forms. One example – land application of bio-char produced via slow pyrolysis – can be combined with biofuel production and can also improve the structure and fertility of soils (see Biochar fact box). The stability of the biochar will depend on the type of feedstock and production conditions as well as soil properties. However, large amounts of bio-char derived C stocks remaining in Amazonian dark earth soils today indicate possible residence times of many hundred years (Figure 3).[16]

Figure 3. *Typical unmodified soil (left), and Terra Preta profile (right). The dark Terra Preta soils have high carbon contents and are very fertile. The organic matter in these soils is also very persistent. It is postulated that the application of organic C from incomplete combustion to improve conditions for agriculture may originally have created these soils. In recent years, the application of biochar from pyrolysis has also attracted interest as an option for the sequestration of C in soils. Photo courtesy of Annette Cowie.*

Other examples, such as the harvesting and burying of trees in trenches or stowing away in above ground shelters[17], would only serve the purpose of cutting off the return pathway to the atmosphere. The alternative – to store the biospheric C in long-lived structures such as buildings and furniture – has the advantage of providing incomes in addition to what can be obtained from potential C markets. The lifetime of C stored in the form of products is long enough to be relevant to near-term GHG targets, but is commonly shorter than what should be required from long-term storage options. One advantage is that the products can be used to generate bioenergy, replacing fossil fuels when they have served their original purpose. However, the total C storage potential is small compared to the estimated C mitigation requirements associated with ambitious stabilisation levels for atmospheric CO_2.[18]

The conversion and management of ecosystems with the aim of creating so-called biospheric C sinks for assimilation of atmospheric C (e.g. afforestation of sparsely vegetated areas and

§ However, plants grown in conditions where other factors (e.g. limitations of rooting volume, light, temperature) restrict growth may not show a sustained response to elevated CO_2.

Figure 4. *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 for sequestration of atmospheric C is a commonly proposed option for climate change mitigation. However, albedo changes may counteract the cooling effect of C sequestration. 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 reflects the local context, i.e. community aspirations and priorities in relation to supply and demand for food, energy services, and material products and also the economic, security and environmental implications. Photo courtesy of Brent Perry.*

various approaches to cropland management to increase soil C content) differs from the concepts for long-term stable storage of C, since the C is still kept within the unstable and dynamic part of the atmosphere-biosphere system[19]. Global and regional capacity, as well as the long-term integrity of such biospheric C sinks, is uncertain since they are sensitive to socio-economic and environmental factors, including climate change, fires, and future LUC.[20]

The focus on the net C effect of establishing new (or protecting existing) high-C ecosystems may overestimate the benefit in terms of net global warming potential (GWP) reduction. Tropical forest systems in particular appear to have significantly reduced capacity to reduce GWP as C sinks due to nitrous oxide (N_2O) emissions, possibly from rapid nitrogen (N) mineralisation under favourable temperature and moisture conditions[21]. Net GWP contributions from wetlands are large, which is primarily due to methane (CH_4) emissions.

As discussed later in the section 'Climate Consequences of Other Changes Associated with LUC', under specific circumstances the warming effect of albedo changes associated with afforestation counteract the cooling effect of most of the C sequested in the forest. The land becomes darker, i.e. less reflective, so albedo is reduced and more solar energy is absorbed leading to increased warming. The cooling effect that is associated with water evaporation to the atmosphere is another factor. Especially in tropical areas this evaporative cooling may compensate for the albedo change effects of afforestation/deforestation. Humans also have a direct influence on the atmospheric water vapour concentration through irrigation – increases in water vapour from irrigation may result in a negative climate sensitivity because of the effect of evaporative cooling at the surface[22].

Due to the difficulties of monitoring and quantifying biospheric C stocks and flows – and the risk that future events may lead to sequestered C being transferred back to the atmosphere – there is concern and debate regarding the permanence and ability to verify different biospheric C sink options.[23] There are also diverging views on whether the creation of C sinks is beneficial or not in the context of climate change mitigation. Critics consider the C sink option a distraction from the necessary transformation of energy systems rather than buying time for developing emission reduction technologies.[24] Additionally, as for bioenergy, there are concerns over effects on local livelihoods and the biodiversity impacts of reforestation and forest management when prioritising C sequestration.[25]

However, like bioenergy plantations, biospheric C sinks that are developed with close attention to local environmental and socio-economic circumstances, and suitably integrated with existing agriculture activities can provide additional benefits such as improved livelihoods, biodiversity preservation, reduced erosion and eutrophication load from agriculture land, improved soil and water quality, rehabilitation of degraded ecosystems and increased crop yield.[26] In some cases the provision of some of these additional benefits may be the primary aim of initiatives and incomes from C sequestration can then be considered a welcome bonus.

In summary, the concepts described above for C re-allocation within the atmosphere-biosphere system do not represent ultimate solutions to the problem of increasing atmospheric C levels. However, the potential of these options are judged sufficiently large to significantly slow the increase in the atmospheric C concentration. They could offer low cost options for – at least temporarily – reducing the atmospheric C levels (or the rate of increase in atmospheric C levels) and be particularly attractive if they lead to additional environmental and/or socio-economic benefits.

Biochar – a potential route for combining bioenergy with soil amendment and carbon storage in soils

One option for use of biomass is slow pyrolysis, which produces both bioenergy, in the form of combustible syngas, and biochar. Biochar is the term given to the solid charcoal-like product of pyrolysis when it is used as a soil amendment. Use of biochar in this way is not a new concept: the highly fertile Terra Preta soils in the Amazon have apparently resulted from the practices of Amerindians in pre-Columbian times, burying charcoal, and wastes in the naturally infertile Ferralsols [a].

A wide range of biomass materials can be used for biochar, including wood waste, manures, and urban green waste. The properties of biochar vary widely depending on the feedstock and pyrolysis conditions. At rates of around 10-20 t/ha, a typical application rate for organic amendments, some biochars have been shown to enhance crop yields and/or reduce fertiliser requirements by more than 50% [b]. These benefits result from the impacts of biochars on soil properties, which include reduced acidity, increased cation exchange capacity, increased water holding capacity, reduced soil strength, and enhanced activity of beneficial microbes [c]. These properties develop over time through interaction between the biochar particles, clays and native soil organic matter [d].

Due to its polycyclic aromatic structure [e] biochar is resistant to chemical and microbial decomposition, with turnover time of hundreds to thousands of years [f]. Thus pyrolysing biomass delays the release of CO_2 to the atmosphere. Furthermore, biochars have been shown in laboratory conditions to substantially reduce N_2O emissions from soil [g]. Consequently, the pyrolysis of biomass to produce biochar can offer multiple benefits in terms of mitigation of GHG emissions: delayed CO_2, decreased N_2O, production of syngas to replace fossil fuels for heat or electricity; reduced fuel for cultivation or irrigation, and reduced manufacture of GHG-intensive nitrogen fertiliser [h]. Additionally, if the feedstock is a biomass material that would otherwise have released CH_4 or N_2O, for example in landfill or manure management, production of biochar can avoid these emissions. One assessment of the theoretical potential mitigation from biochar applications estimated that global implementation of biochar systems could reduce global greenhouse gas emissions by around 1.8 Gt CO_2^{eq} per annum, or 12% of current anthropogenic CO_2^{eq}, with 50% of the reduction from C sequestration, 30% from replacement of fossil fuels and 20% from avoided emissions of CH_4 and N_2O [i].

Pyrolysis is a particularly suitable option for biomass sources not well suited to other bioenergy applications due to high moisture content or presence of soil or elements such as P and Ca which would be considered contaminants in most energy conversion processes, but which can be highly beneficial in a soil amendment. Biochar and bioenergy systems could be integrated, so that biochar is applied to fields being used for energy, to enhance the yields of biomass.

It is critical that biomass for biochar is sourced from sustainable supplies, and that biochar is produced in a processing facility where particulate and gaseous emissions are controlled: the gas should be utilised for energy, or, as a minimum, flared to avoid emission of methane. In the same way that bioenergy has been responsible for indirect land use change; there is a risk that widespread adoption of biochar could lead to deforestation through direct or indirect land use change. Measures being developed to address this issue for bioenergy could perhaps be applied to biochar systems, to ensure sustainability.

Small-scale biochar systems, suitable for supplying a household's energy and biochar for soil amendment, could make a major contribution to sustainable development in developing countries. Biochar is particularly effective in boosting soil fertility in dryland regions, especially in acidic, highly weathered tropical soils and in soils that are degraded, such as through long-term cultivation or overgrazing. Because biochar can be produced at low cost from locally-available biomass, and reduces the need for chemical fertilisers, biochar systems can be readily adopted by resource-constrained landholders, and have the potential to enhance household incomes [j].

See page 54 for the references on biochar.

Options for Influencing the Amount of Carbon Present in the Atmosphere-Biosphere System

There are two principal means of influencing the amount of C present in the atmosphere-biosphere system: (i) preventing fossil C emissions entering the atmosphere-biosphere system in the first place and (ii) removing C that is already present in the atmosphere-biosphere system.

Preventing fossil carbon emissions to the atmosphere-biosphere system: Fossil C can be prevented from being injected into the atmosphere-biosphere system by: (i) reducing the use of fossil fuels, or shifting to less C-intensive fossil fuels; and (ii) preventing fossil C emissions to the atmosphere while using fossil fuels.

There are numerous studies on how to achieve a reduction in fossil fuel use (and/or shift to less C-intensive fossil fuels) but it is beyond the scope of this report to summarise these.* However, it can be concluded that among the options at hand – either energy efficiency/conservation or shifts to other primary energy sources – bioenergy is often concluded to be one of the more important. Many scenarios show increased use of biomass for energy with increasingly ambitious GHG mitigation targets, which indicate that bioenergy could play an important role in contributing to the long-term objective to hold the increase in global temperature below 2°C (Copenhagen Accord).

Biomass (mainly wood) presently contributes some 10% of the global primary energy supply and is the most widely used renewable primary energy source. Assessments indicate that there is significant potential to expand biomass use and that bioenergy can become one of the major primary energy sources in the future – see the section 'Biomass Resources'.

The alternative way – preventing fossil C emissions to the atmosphere while using fossil fuels – relies on technologies for CCS, which can be applied in stationary energy plants where the C is captured from the smoke stacks and transferred to geologic CO_2 storage reservoirs such as saline aquifers (which have the largest storage potential), depleted oil and gas reservoirs, and also sequestered in association with enhanced oil recovery and in deep unminable coal seams where coal-bed methane production can offset some of the storage cost[27]. CO_2 injection to the ocean has been proposed as an alternative storage option[28].

CCS is expected in the first instance to be cost-effective in large (around 1,000 MW) coal-fired power plants that are running in base load. A power plant equipped with a system for C capture would be subject to an energy penalty of typically less than 10% and would avoid CO_2 emissions to the atmosphere by about 80-90% compared to the equivalent plant without CCS[29]. There is also the possibility of producing liquid and gaseous fuels (e.g. FT diesel, methanol and DME, commonly designated synfuels) from coal where the C not ending up in the fuel is captured and stored. Such synfuel production is based on gasification and allows for co-generation of electricity, plus the surplus heat can be made useful in other industrial processes or for district heating.

However, the production and use of such fossil synfuels would still result in fossil C emissions that are similar to those from gasoline and diesel (depending on the C content of the synfuel)[30]. The production of hydrogen would avoid the C emissions associated with the synfuels combustion.

There are still technical, economic and not the least legal/political uncertainties surrounding CCS. Long-term CO_2 storage integrity is one important aspect that warrants close attention since the climatic consequences of CCS-associated CO_2 leakage may be grave. For storage to be effective the storage residence time must typically be greater than 1,000 years, i.e. seepage rates below 0.1% per year[31]. Geologically stored CO_2 will be dissolved in water and also undergo mineralisation processes, which are slow processes but which nevertheless reduce the probability of leakage over time. Depending on discount rate, CCS is found to remain a competitive mitigation option even at higher CO_2 leakage rates (1% per year)[32], although it is probable that such high leakage rates would not be acceptable if detected[33]. Monitoring to secure the long-term safety of CO_2 storage is thought to be possible but work is needed to develop efficient and reliable detection and risk assessment methods to certify storage sites[34].

Alternative storage options that avoid leakage risks and do not require post-storage monitoring, mimic naturally occurring weathering processes, where calcium or magnesium from silicate minerals is bound with CO_2 to form environmentally benign and stable calcium/magnesium carbonates[35].

Removing carbon from the atmosphere-biosphere system: There are several options for removing C from the atmosphere and storing it in other pools for a long time[36]. Some of these employ technologies that are also used for CCS. Air capture is a technical process that captures CO_2 directly from ambient air and produces clean CO_2 that can be stored in geological reservoirs as described above for the case of CCS. Compared to CCS, when applied to large point sources, air capture has the advantage of avoiding the need for piping to transport the CO_2 to storage sites, and the geographic flexibility makes it possible to optimise the location in relation to the availability of suitable CO_2 storage sites and of renewable energy to meet energy needs[37].

Various means of accelerating geochemical weathering can also remove CO_2 from the atmosphere and store the C in the ocean[38]. The burial of crop residues in the deep ocean represents another option for transferring C from the atmosphere to the ocean, which instead uses photosynthesis as a mechanism for removing CO_2 from the atmosphere. The biomass that is extracted and sunk in the ocean eventually becomes buried by sedimentation. Oceanic permanent sequestration of crop residues takes advantage of two characteristics of the deep ocean: (i) minimal mixing between the deep sea waters and the upper oceanic layer in contact with the atmosphere, and (ii) the relative stability of terrestrially derived organic matter in the sediments compared to marine organic matter, due to the cold temperature, limited oxygen availability, and apparent lack of a marine mechanism for the breakdown of lignocellulose[39].

** See the IEA Energy Technology Perspectives and World Energy Outlook series.*

When combined with CCS, bioenergy can provide energy services while generating so-called 'negative CO_2 emissions', i.e. a net flow of C from the atmosphere to geologic CO_2 storage reservoirs[40]. Capturing CO_2 from biomass-based processes such as sugarcane-based ethanol mills and chemical pulp mills, is one possibility that has been suggested, and biomass could also be used as fuel in power generation in association with capture[41]. However, since the economics of CCS assume large-scale units and high thermal efficiency, CCS applications may not be straight forward if considering biomass-only fired units, due to the logistic and other challenges associated with managing large biomass flows and the risk of high temperature corrosion under the boiler operating conditions required to reach high conversion efficiency (high steam pressure and temperature).

One way to introduce biomass in CCS power plant schemes initially could be to co-fire biomass with coal, where relatively low biomass fractions (typically 10% of the fuel mix on an energy basis) would reduce the risk of high temperature corrosion[42]. The production of synfuels from coal described above could also make use of biomass as feedstock. Introducing biomass in the feedstock mix would lower the fossil C emissions, with net GHG outcome depending on the biomass proportion in the feedstock mix and biomass supply chain emissions[43].

In contrast to several of the options for preventing fossil C emissions to the atmosphere, options for actively removing C from the atmosphere are at an early stage of development and there are significant uncertainties regarding possible negative impacts as well as the practical and economic applicability on scales large enough to make a significant contribution to climate change mitigation[44]. The same conclusion is valid for concepts aimed at reducing solar radiation input to the climate system to compensate for the additional long-wave infrared radiation from GHGs, such as the introduction of additional aerosols into earth's stratosphere[45]. Thus, these options cannot be considered substitutes for comprehensive mitigation measures that primarily aim at reducing the fossil C emissions to the atmosphere.

To conclude, the most important option for society at present is to reduce the emissions of fossil C to the atmosphere. This requires a radical change in the global energy system. Reducing energy consumption and increasing the bioenergy supply are among the major options for reducing fossil C emissions to the atmosphere.

BIOMASS RESOURCES

Biomass (mainly wood) currently contributes some 50 EJ/year, or 10% of the global primary energy supply and is the most widely used renewable energy source (Figure 5). 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.

Realising high potentials requires far-reaching changes in present land use. Providing several hundred EJ/year of biomass 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

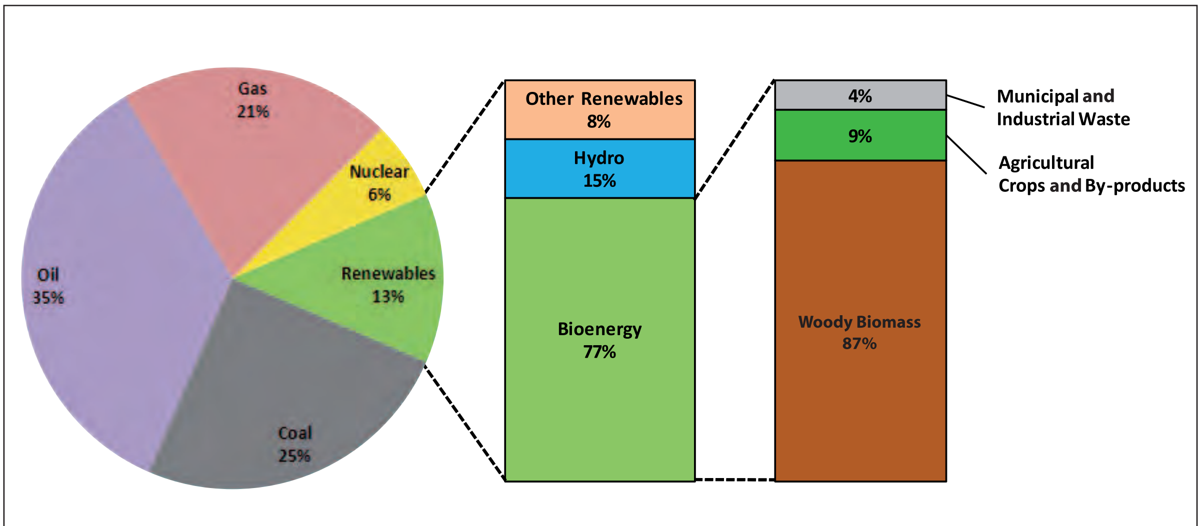


Figure 5. *Share of bioenergy in the global primary energy supply. For further information, see IEA Bioenergy, 2009a.*

Figure 6. *Global city lights. The brightest areas of the earth are the most urbanised, but not necessarily the most populated. (Compare western Europe with China and India.) Cities tend to grow along coastlines and transportation networks. Courtesy Marc Imhoff of NASA GSFC and Christopher Elvidge of NOAA NGDC. Image by Craig Mayhew and Robert Simmon, NASA GSFC.*

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.

More information about biomass resources can be found in the report 'Bioenergy – a Sustainable and Reliable Energy Source' published by IEA Bioenergy (See Recommended Reading, page 53).

LAND USE CHANGE

Drivers of Land Use Change

As noted above, LUC emissions have contributed roughly one-third of the accumulated anthropogenic C emissions to the atmosphere since 1850. Historically, agricultural expansion has been the main cause of LUC, but other activities can also claim land. Cities cover less than 0.5% of the world's surface[46], but commonly claim fertile soils, since human settlements have often been established in areas where cultivateable land could provide local food supply. As will be further discussed below, cities tend to grow along coastlines and transportation networks, and establishment of new infrastructure – in particular roads – in areas with low population density can bring with it an inflow of migrants that cause additional land conversion as they establish new agriculture and forest extraction activities.

Energy-related projects other than bioenergy projects also play a role in LUC. There is an impact on land use related to the construction and operation of all energy generating facilities, including emerging renewable options such as wind and solar power. The land requirement and impact (including visual impacts) of on-shore wind turbines depend on the size and type of installation. Estimates indicate that some 10-30 ha per MW may be required (depending on the local terrain)[47]. Assuming an average load factor at about 30%, this corresponds to roughly 250-800 MWh ha^{-1}. However, only a small percentage of this area is needed for turbine foundations, roads or other infrastructure, and wind power does not crowd out land use activities in the same way as some other energy options[48]. For instance agriculture can coexist with wind power in many ways. Solar, thermal and PV power systems can be integrated into buildings and other structures, although there are also solar power installations that lock away land areas from other uses. However, these use less land per unit of electricity output than most other options. Among the best locations for solar power plants are deserts or other land areas with few other human uses.

Hydropower projects can submerge large areas as reservoirs are established for water storage. Examples of hydropower dams having reservoirs with large surface areas include the Three Gorges Dam in China, the Akosombo Dam (Lake Volta) in Ghana, Churchill Falls in Canada, the Guri Dam in Venezuela, and several Brazilian dams including the Itaipu Dam located at the Paraná River on the border between Brazil and Paraguay (Figure 7).

As can be seen in Table 1, the estimated annual electricity output per unit area varies considerably among hydropower plants, which is not only due to the power density (W/m^2) but also depends on the load factor. Average power density for the entire hydroelectric potential of the Amazon Region is estimated to be about 1 W/m^2 [49], which would translate into an electricity output at about 53 MWh $ha^{-1}yr^{-1}$, assuming

Figure 7. *Itaipu Dam, located at the Paraná River on the border between Brazil and Paraguay. The Itaipu's reservoir is the seventh largest in Brazil, but has the best relation between electricity production and flooded area – see Table 1. Source: www.itaipu.gov.br*

an average load factor at 0.61 (average for the hydropower stations in Table 1). For comparison, a bioenergy plantation yielding 15 dry Mg ha^{-1} yr^{-1} (18 GJ Mg^{-1}) could provide about 23 MWh $ha^{-1}yr^{-1}$ if the harvested biomass was used in a power plant with 30% conversion efficiency. It should be noted that many hydropower stations have significantly higher power densities and load factors.

Hydropower projects may entail the relocation of local communities living within or near the reservoir or construction sites, and can also affect downstream communities (in positive or negative ways). Displacement as well as resettlement schemes can have both socio-economic and environmental consequences including those associated with LUC for establishment of new agricultural land[50]. Dam construction also stimulates migration into the affected region, and large influxes of people can lead to deforestation and other negative impacts from increased cattle production and other land uses[51].

Thus, besides the flooding of areas, there are other LUC effects associated with hydropower dams that are difficult to quantify, not the least since they may take place a long time after the completion of hydropower projects. For instance, the Three Gorges Dam project has involved the resettlement of more than one million people and it has been estimated that four million of the 16 million people living in the reservoir area may have to be relocated in the years following the project completion[52].

In addition, and relevant in the context of climate change, the flooding of land causes CH_4 emissions due to the anaerobic decomposition of submerged vegetation and there is also a loss in C sequestration into growing vegetation in the flooded area.[53] The magnitude of GHG emissions and C sequestration losses caused by inundation can be significant, but the uncertainty in the quantification of such emissions is high.[55] GHG emissions can also occur during the final phase of the hydroelectric power plant's life associated with the fate of sediments accumulated in the reservoir during the operation of the power plant. The carbon in the accumulated sediments in the reservoir may be released to the atmosphere as CO_2

Table 1. Selected hydroelectric power stations having large reservoir areas.

Country	Name	Flooded area km^2	Capacity, MW (load factor)	Annual electricity output[14] MWh $ha^{-1}yr^{-1}$
Brazil	Sobradinho Dam	4214[1]	1050[2]	13*
Brazil	Tucuruí Dam	2850[3]	8125[3] (0.30)	75
Brazil	Balbina Dam	2360[1]	250[4]	6*
Brazil	Engineer Sérgio Motta Dam5	2250[5]	1540[5] (0.75)	45
Brazil	Serra da Mesa	1784[1]	1275[6] (0.56)	35
Brazil	Furnas Dam	1473[7]	1216[7]	43*
Brazil	Itaipu Dam	1350[1]	14 000[8] (0.73)	667
Canada	Churchill Falls	5698[9]	5428[9] (0.74)	61
China	Three Gorges Dam	1045[10]	18 200[10] (0.50)	766
Ghana	Akosombo Dam (Lake Volta)	8502[11]	1020[11]	6*
Venezuela	Guri (Simón Bolívar)	4250[12]	10200[12] (0.53)	111
Argentina, Paraguay	Yaciretá	1650[13]	3100[13] (0.74)	121

1 www.ib.usp.br/limnologia/Represa/Maioresrepresas.htm (retrieved 19 March 2011)
2 www.industcards.com/hydro-brazil-ba.htm
3 en.wikipedia.org/wiki/Tucuruí_Dam
4 en.wikipedia.org/wiki/Balbina_Dam
5 Also named Porto Primavera Dam. Companhia Energetica de Sao Paulo (CESP) Sustainability Report 2009
6 en.wikipedia.org/wiki/Serra_da_Mesa_Dam
7 en.wikipedia.org/wiki/Furnas_Dam
8 www.itaipu.gov.br/en
9 en.wikipedia.org/wiki/Churchill_Falls_Generating_Station
10 en.wikipedia.org/wiki/Three_Gorges_Dam
11 en.wikipedia.org/wiki/Akosombo_Dam
12 en.wikipedia.org/wiki/Guri_Dam
13 en.wikipedia.org/wiki/Yaciretá_dam
14 Numbers marked * were calculated from the capacity number using the load factor 0.61, which was the average for the hydropower stations in the table that provided information required for calculating specific load factors.

Table 2. Annual output per unit of land and GHG emissions associated with the land disturbance for the supply of conventional and unconventional fossil fuels[56]. For comparison: 1 PJ ha^{-1} of oil output would be equivalent to almost 700,000 MWh ha^{-1} of electricity output if oil is used to generate power with an efficiency of 40%[#], thus producing electricity output per land unit orders of magnitude larger than the hydropower projects presented in Table 1. An estimate of GHG emissions associated with military activities to secure USA oil imports from the Persian Gulf is also given[57].

Fossil fuel recourse/associated activity		Annual fossil fuel output per unit land, PJ ha^{-1}	Associated GHG emissions, g CO_2^{eq} MJ^{-1}
California oil	Historical land disturbance 1919-2005[1]	0.79 (0.48-2.6)	0.09 (0.02-0.25)
	Marginal land disturbance in 2005[2]	0.55 (0.33-1.8)	0.13 (0.03-0.35)
Alberta oil	Historical land disturbance 1948-2007[1]	0.33 (0.16-0.69)	0.47 (0.12-1.98)
	Marginal land disturbance in 2007[2]	0.20 (0.092-0.40)	0.78 (0.2-3.39)
Oil sands – surface mining		0.92 (0.61-1.2)	3.9 (0.83-10.24)
Oil sands – in situ		3.3 (2.2-5.1)	0.07 (0.0-0.23)
Military emissions for securing USA oil imports from the Persian Gulf			98
Coal – surface mining[3]		0.01-0.29	
Coal – underground mining[3]		0.02-5.48	

[1] The number of well pads per oil field (including active and shut in production and injection wells and estimated abandoned and unrecorded wells) was multiplied by the estimated area disturbed per well pad and divided by the cumulative production for each oil field during the given period.

[2] The number of wells drilled in 2005 and 2007, respectively, was multiplied by the area disturbed per well pad and divided by crude production in the respective year.

[3] Direct land transformation during mining

and CH_4 upon decommissioning of the dam.[54] Uncertainties in quantifications of these emissions are high but estimates indicate that they can make up a significant part of the cumulative GHG emissions of hydroelectric power plants.[54]

There are also LUC emissions associated with the extraction of fossil fuels. Surface mining of coal (Figure 8), 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. Direct LUC emissions are estimated to contribute a relatively small part of total life cycle GHG emissions from conventional and unconventional oil (Table 2): less than 1% for California crude and *in situ* oil sands production; 0.1-4% for Alberta conventional oil; and 0.9-11% for surface mining of oil sands. Emissions released from land disturbed by fossil fuels can be comparable or higher than biofuels, but the higher energy yield of oil production leads to lower GHG emissions per unit of biofuel/petroleum fuel output.

Studies further assess non-GHG impacts of extracting fossil resources, such as habitat loss and ecosystem fragmentation[58] and show that many of the fossil reserves are located in fragile or biodiverse areas, e.g. the world's three largest unconventional oil deposits are located in areas of high value for ecosystem integrity and biodiversity[59]. In this context, the 1989 Exxon Valdez oil spill and the 2010 Deepwater Horizon oil spill represent well-known examples where the environmental impacts have affected aquatic ecosystems and terrestrial ecosystems close to the water.

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, causing indirect emissions[60]. It has also been proposed that GHG emissions associated with military activities motivated by energy security considerations should be at least partly allocated to fossil fuels[61]. Estimating what fraction of military activities – and associated GHG emissions – that should be allocated to energy security involves speculation and disputable assumptions. Even so, estimates of the military emissions associated with securing gasoline from Middle East oil are similar in magnitude to the direct GHG emissions of gasoline use, indicating that these GHG emissions can indeed be significant (Table 2).

Figure 8. *Example of dLUC caused by an energy supply project. Brown-coal mine Garzweiler (BraunkohletagebauGarzweiler) in Germany. Photo courtesy of D-Luftbild.de.*

 # An international comparison of energy efficiency of fossil power generation found that average conversion efficiency was about 38% for oil based power in Australia, China, Denmark, Finland, France, Germany, India, Ireland, Japan, Norway, South Korea, Sweden, United Kingdom and United States (Energy Policy 35(7): 3936-51). However, it should be noted that oil has benefits for load following and backup power applications rather than in base load generation.

Nuclear power has land use impacts associated with mining operations, but the major issue is associated with the risk that a nuclear accident leads to land contamination due to release of radioactive material. The 1986 Chernobyl disaster in the Ukraine resulted in large amounts of radioactive contamination being spread across Europe. Most of the fallout concentrated near Belarus, Ukraine and Russia, where some 125,000 km^2 of land (more than a third of which was in agricultural use) was contaminated. At least 350,000 people were resettled away from these areas, and agricultural products, livestock, and soil were contaminated, making land unusable for humans[62].

The long-term consequences of the recent events in Japan, where the Fukushima nuclear power plant suffered major damage from an earthquake and subsequent tsunami (11 March 2011), cannot yet be determined. Current estimates of the direct radiation levels from the Fukushima plant are significantly lower than those that occurred during the Chernobyl accident, but reports of radionuclides in soil, water and food products still raise concerns over possible consequences for Japan's ecology and agriculture.

Nevertheless, LUC is linked to bioenergy to a greater extent because of its close association with agriculture and forestry. Agricultural expansion has been, and continues to be, the major driver of LUC and the associated emissions. Globally, roughly half of the earth's ice-free land surface has been transformed to human use (primarily to agricultural land to feed a growing population) and much of this expansion has taken place on forest ecosystems[63]. A large part of the remaining forests are heavily influenced by humans; it is estimated that less than a quarter of earth's ice-free land surface remains as wildlands[64].

Figure 9. *Contrasting drivers of LUC in agriculture. Top photo: Agriculture settlements east of Santa Cruz de la Sierra, Bolivia in an area of tropical dry forest. Bottom photo: Forests under conversion pressure for farming and cattle ranching in an area south of the Amazon River (State of Pará). Picture Source: NASA - National Aeronautics and Space Administration.*

More than 80% of new tropical croplands in the 1990s replaced mature or degraded forests[65]. Agricultural expansion takes place in response to a complex set of interconnected biophysical, socio-economic, and institutional factors and these vary in importance from one country to the other – and also within countries. As an illustration, Figure 9 shows two contrasting cases of agriculture-driven LUC. The top photo shows agriculture settlements east of Santa Cruz de la Sierra, Bolivia in an area of tropical dry forest. Since the mid-1980s, the resettlement of people from the Altiplano (the Andean high plains) and a large agricultural development effort called the Tierras Baja project has caused substantial deforestation. Each agricultural 'pin wheel' pattern is centered on a small community. The communities are then spaced evenly across the landscape at 5 km intervals. Roadways can be seen connecting each town centre. The bottom photo shows forests under conversion pressure for farming and cattle ranching in an area south of the Amazon River (State of Pará). Deforestation is especially evident in the lower right of the image, which is virtually denuded except for thin stretches of vegetation that remain along the banks of the creeks that feed the Araguaia River, which runs southwest from the center of the image's right edge. The brown water is likely an indication of sediment that washes unchecked into the river. In the heart of the remaining forest, a road deviates southward from the course of the Tapajós River (upper left, beneath the smoke), bringing additional deforestation. While State or Federal level policies and projects more indirectly induce LUC in this case they are still important drivers behind deforestation.

Almost 150 Pg C was emitted to the atmosphere as a consequence of LUC during the period 1850-2000 (Figure 2). This is roughly one-third of the total accumulated anthropogenic C emissions during this period and most of these LUC emissions were caused by the conversion of forests to agricultural land. About 55% of these LUC emissions took place in the tropics. About 1.5 Pg yr^{-1} of biotic C is presently emitted to the atmosphere, mainly due to deforestation in tropical regions (Figure 10). South and Central America have had the largest LUC emissions since 1960 and emissions in this region were above 0.9 Pg C yr^{-1} in 1986-1991. Since then, the emissions have declined and they are now about 0.6 Pg C yr^{-1}, similar to South and Southeast Asia. Together, these two regions presently make up about 80% of total LUC emissions. In tropical Africa, LUC emissions have steadily increased and reached 0.2 Pg C yr^{-1} during the 1980s. As can be seen in Figure 10, LUC emissions in this regions have increased further and are now well above 0.2 Pg C yr^{-1}.

The net C fluxes between the atmosphere and the biosphere are presently significantly lower in other regions. On a net basis, both North America and Europe have long been net sinks of atmospheric C due to forest regrowth. The former USSR region and China have had substantial reductions in LUC emissions since 1960 (Figure 10). It should be noted that the C flux estimates in Figure 10 do not consider the effects of CO_2 fertilisation. As noted above, CO_2 fertilisation is estimated to be one major cause of the terrestrial biosphere current status as a net sink of C, although – as also noted above – uncertainty exists regarding sink strength and permanence[66].

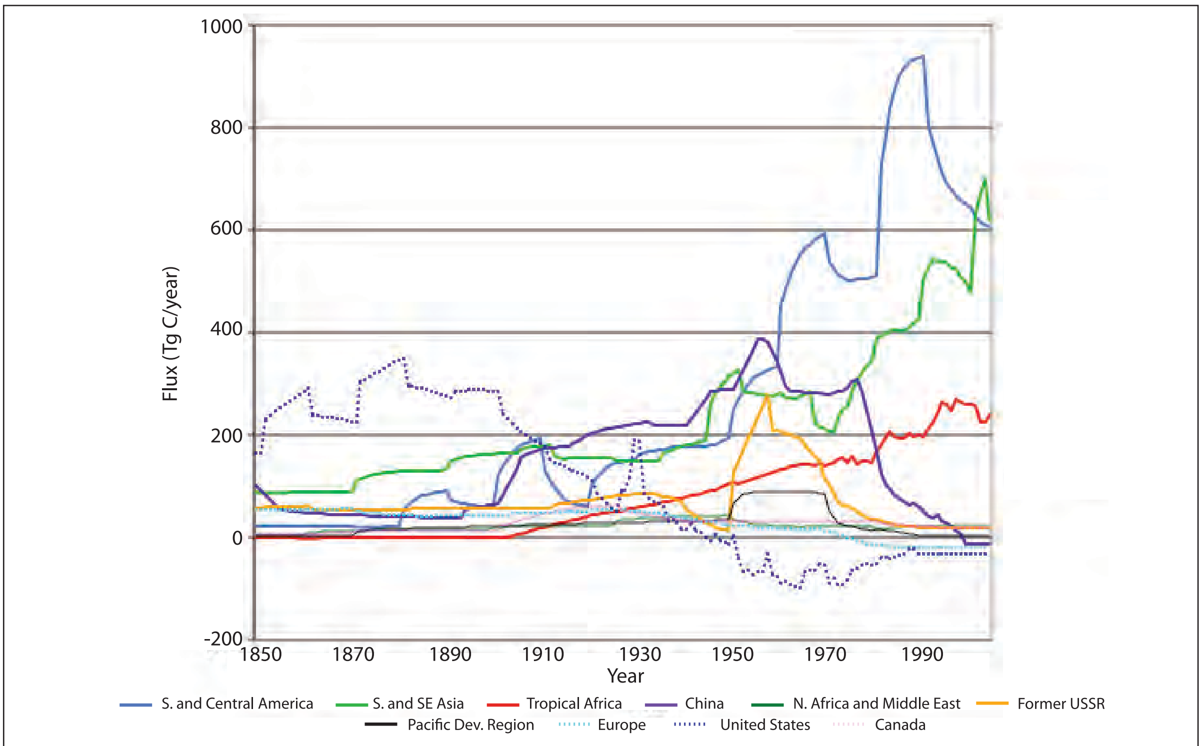


Figure 10. *Annual net LUC emissions to the atmosphere 1850-2005[67]. The net C flux shown includes both C emissions from deforestation and sinks of C in forests recovering from harvests or agricultural abandonment. Includes C fluxes resulting from ecosystem conversion or harvest, i.e. the expansion and contraction of croplands and pastures, plantation establishment, and harvesting of wood. The modelling has taken into account both the initial removal and oxidation of the carbon in the vegetation and the subsequent regrowth and changes in soil carbon. Variations in climatic factors, CO_2 concentrations, or other elements of environmental change were not considered in the modelling.*

Bioenergy and Land Use Change

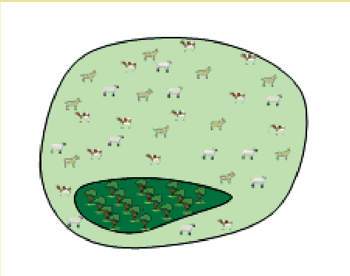
Currently, less than 1% of global agricultural land is used for cultivating biofuel crops, and LUC associated with bioenergy represents a very small percentage of overall changes in land use. However, since bioenergy is the primary energy source most closely associated with LUC, policy makers and other stakeholders have particularly focused attention on how LUC emissions affect the climate benefit of increasing levels of bioenergy. This is also motivated by many studies that have concluded large areas will have to be dedicated to bioenergy plantations in order to realise the higher assessed potentials for bioenergy (see the section 'Biomass Resources').

The discussion about the links between bioenergy and LUC commonly makes a distinction between direct and indirect LUC:

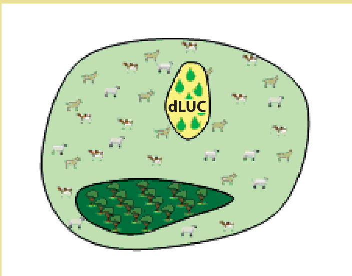
- dLUC involves changes in land use on the site used for bioenergy feedstock production, such as the change from food or fibre production (including changes in crop rotation patterns, conversion of pasture land, and degradation of managed forests) or the conversion of natural ecosystems.
- iLUC refers 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 agricultural 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.

Figure 11 shows an illustration of the links between dLUC and iLUC for a particular case where grassland that was previously used for livestock production is converted to bioenergy plantations – dLUC. The resulting displacement of the previous land users and the loss of food production are here assumed to lead to LUC outside the system boundary for the bioenergy system – iLUC.

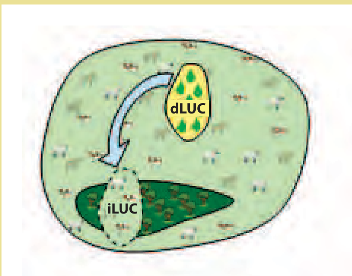
The iLUC taking place in this illustrative example is in the form of deforestation for pasture establishment, which might



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



The introduction of 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 macro-economic pressure induces increased productivity.

Figure 11. *Examples of direct and indirect land use changes arising as a consequence of a bioenergy project.*

take place both because the displaced actors re-establish their businesses in a previously forested area and because of the macro-economic effects: the lost meat and dairy production leads to lower supply in relation to the given demand, which drives up prices and thereby stimulates increased animal production – in this case through expansion of pastures into a forest.

In reality, part of the increased animal production will likely be accomplished through intensification, and the displaced actors may turn to activities other than those connected to cattle ranching or other land use. The biofuel production in itself often generates protein rich by-products that are suitable for animal feed, displacing other animal feed production and thereby reducing the net LUC effect of the bioenergy project. If appropriate types of biofuel plants are – spatially or temporally – integrated with food production, positive effects such as reduced erosion and increasing soil C can improve food productivity. This, in turn, reduces the land required to meet the particular demand for food.

Bioenergy does not always cause LUC. The use of post-consumer organic waste and agricultural/forest industry by-products can avoid LUC and related GHG 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. Furthermore, exploitation of harvest residues may result in decreasing soil productivity and lower yields leading to cropland expansion to compensate for the lost production. On the other hand, deposited organic waste may cause methane emissions as they decompose, leading to a greater climate impact than if burned directly, albeit with a different time profile (see also the section 'Options for mitigating LUC associated with bioenergy').

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[68]. Observations also indicate that old forests, which commonly have been presumed to be neutral in their C exchange with the atmosphere, can be net C sinks[69] and 'foregone carbon sequestration' has been proposed as a possible consequence of LUC that also needs to be considered when such ecosystems are converted to biomass plantations. But the future CO_2 assimilation can also be increased, for instance when sparsely vegetated land is forested.

Delayed GHG emissions and sequestration of carbon in growing forests can be considered a benefit in relation to near-term GHG targets and can also be a relevant factor in longer-term accounting in regions where biomass degradation is slow (e.g. boreal forests). Thus, the much discussed trade-off between the two principal land use options – to produce biomass for energy or to manage the land as a carbon store – also applies to some residues and waste streams that would retain organic carbon for a significantly longer time than if used for energy, e.g. forest residues. As when considering land use for bioenergy vs for sinks management, there is a need to consider the long-term fate of biomass that is not harvested for bioenergy. Fires, insect outbreaks and other natural disturbances can quickly convert a forest from net sink to emitter[70]. For example, about 100 million m^3 of wood was lost in the Gudrun storm in the Baltic Sea region in January 2005. Although a large part of the wood can be recovered, insect attacks and fires may cause large C stock losses after events of this kind.

In forested lands susceptible to periodic fires, good silviculture practices can lead to less frequent, lower intensity fires and can improve site conditions for replanting leading to higher growth and productivity, i.e. accelerated 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. In one noteworthy example, mountain pine beetle killed wood in North American forests is a fire hazard and will – if not harvested – either burn in wild fires or decay and release carbon back to the atmosphere. The removal of such wood can instead provide a feedstock for bioenergy applications[71].

Forests and other natural ecosystems may in addition become converted to other land use later, e.g. to provide food. It is therefore necessary to consider the likelihood of such later events when considering foregone carbon sequestration, which makes quantification a complex task. The quantification of altered CO_2 assimilation capacity thus requires that a 'baseline' land use development is defined, which requires model-based approaches similar to those used for quantifying iLUC effects. Methodology approaches for quantifying LUC and associated GHG emissions are discussed further in the section 'Bioenergy and Climate Change Mitigation'.

When residues and waste are used for bioenergy, LUC may also be avoided or mitigated if the production of biomass for energy can be integrated with the existing land use so as to reduce the displacement effect (Figure 12 shows one example of such integration). Ideally, wisely implemented bioenergy systems may stimulate increased productivity in other land use and in this way avoid land use displacement. The production of bioenergy feedstocks on marginal or degraded lands, where productive capacity has declined temporarily or permanently, represents another option for reducing LUC effects and potentially obtaining additional benefits such as C sequestration in soils and above ground biomass and improved soil quality over time. These options are discussed further in the section 'Options for Mitigating LUC Associated with Bioenergy'.

Figure 12. *Integration of Eucalyptus spp. 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.*

BIOENERGY AND CLIMATE CHANGE MITIGATION

Production and use of bioenergy influences global warming through:

- emissions from the bioenergy chain including non-CO_2 GHG and fossil CO_2 emissions from auxiliary energy use in the biofuel chain;
- GHG emissions related to changes in biospheric carbon stocks often caused by associated LUC (section 'GHG Emissions Reduction in the Presence of LUC');
- other non-GHG related climatic forcers including particulate and black carbon emissions from small-scale bioenergy use[72]; aerosol emissions associated with forests[73]; and changes in surface albedo (section 'Climatic Consequences of Other Changes Associated with LUC'); and
- effects associated with other changes that arise due to the bioenergy use, such as price effects on petroleum influencing consumption levels.

The net effect is the difference between the influence of the bioenergy system and of the – often fossil-based – energy system that is displaced. Thus, 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. Studies of environmental effects, including those focused on GHG emissions balances, usually employ methodologies in line with the ISO 14040:2006 and 14044:2006 standards for life cycle assessment (LCA), which define the principles, framework, requirements, and guidelines for conducting an LCA study.

IEA Bioenergy Task 38, which has the objective of assisting the implementation of forestry, land use and bioenergy options to reduce GHG emissions through methodological work[±], has developed a specific standard methodology framework for assessing GHG balances of biomass and bioenergy systems (Figure 13)[74]. It employs methodologies in line with the ISO 14040:2006 and 14044:2006 standards for LCA. Critical steps include: (i) system definition (spatial and dynamic system boundary); (ii) definition of functional units; (iii) reference flows and indicators; and (iv) the selection of allocation methods for energy and material flows that cross the system boundary.

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;
- 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 CO_2 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.

The handling of uncertainties and sensitivities related to the data used may have a significant impact on the results. Development of biomass production and conversion technologies makes old LCA studies outdated and 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 full-scale experimental information. In addition, many biofuel production processes create multiple products. Bioenergy systems can be part of cascading biomass cycles in which co-products and biomaterials themselves are used for energy after their useful life[75]. 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 long time periods and take place at different geographical locations[76].

N_2O emissions vary considerably depending on environmental and management conditions, including soil water content, temperature, texture, carbon availability, and, most importantly, N fertiliser input[77]. The methodology used can also influence the results of assessments. The standard practice is to use emission factors to quantify N_2O emissions as a function of N fertiliser input and there has in recent years been debate about the correct value for these emission factors. Crutzen *et al.* (2007)[78] proposed that N_2O emissions from fresh anthropogenic N are considerably higher than IPCC's recommended Tier 1 method-based results, and that N_2O emissions from biofuels consequently have been underestimated by a factor of two to three. However, the difference is due to the fact that the estimates of IPCC Tier 1 and Crutzen *et al.* use different accounting approaches. About one-third of agricultural N_2O emissions are due to newly fixed N fertiliser and two-thirds takes place as N is recycled internally in animal production or used as organic fertilisers (dung and plant residues)[79]. Using N_2O emissions factors proposed by Crutzen *et al.* makes a specific bioenergy plantation responsible for all N_2O emissions taking place subsequently, i.e. also for the part of the applied N that is recirculated into other agriculture systems where it substitutes for other N input. Recent modelling efforts support the conclusion that emission factors based on Crutzen *et al.* overestimate the emissions[80]. Even so, N_2O emissions can have an important impact on the overall GHG balance of biofuels.[81]

Most studies of CH_4 emissions from ecosystems have naturally focused on wetlands since these are the hotspots of CH_4 production. Until recently, biological CH_4 formation has been associated exclusively with anoxic environments and methanogenic activity, but there is growing evidence

± *For more information about IEA Bioenergy Task 38, visit www.ieabioenergy-task38.org.*

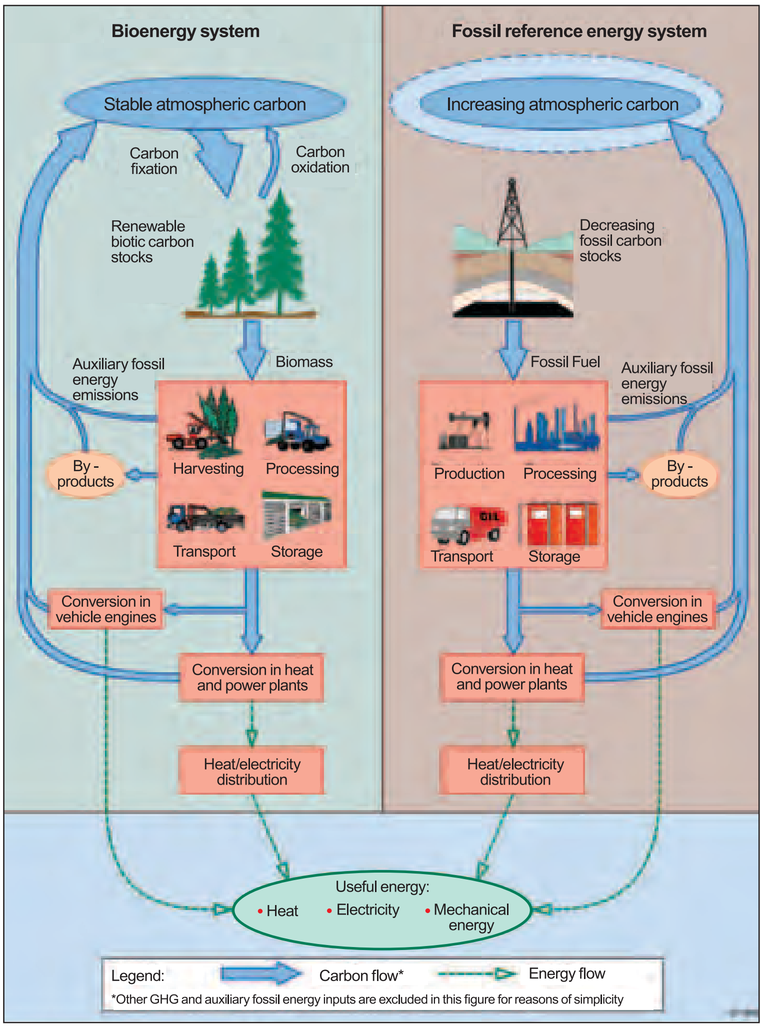


Figure 13. *Task 38 standard methodological framework for comparing bioenergy and fossil energy system. For further information, see www.ieabioenergy-task38.org*

that terrestrial plants can also emit CH_4 under aerobic conditions[82]. Drier upland ecosystems are normally net sinks for atmospheric CH_4 since the CH_4 consumption exceeds the CH_4 production. But depending on soil water content some forests may switch to become CH_4 sources. Pastures and cropland may also be net sources or sink for CH_4. There are indications that higher temperatures and water stress enhance CH_4 emissions from commonly cultivated plants and that CH_4 emission may become higher due to the global climate change in warmer and drier environments, despite the mitigating effects of rising atmospheric CO_2.

Conversion of land use from cropland or pasture to woody energy crops may reduce emissions of CH_4, while conversion of forests to annual energy crops is likely to increase net CH_4 emissions. The lower CH_4 oxidation, or higher emission, in cropland and pasture soils is due to higher soil nitrogen, and disturbance. Within a LCA study, soil CH_4 fluxes usually make a relatively small contribution to total life cycle GHG emissions of the bioenergy chain.

Another 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. The possible LUC associated with these replaced energy systems also needs to be considered in the evaluation. This adds to the challenge since LUC effects associated with fossil and other conventional energy supply have not been studied extensively. One way to address all uncertainties is to combine several LCA models and/or Monte Carlo analysis to investigate bioenergy system uncertainties and levels of confidence for results[83].

Most bioenergy system LCAs to date are attributional and concentrate on existing bioenergy systems – stationary energy and 1st generation biofuels – and to conditions and practices in Europe or North America, although studies are becoming available for other countries, for example Brazil, China and Thailand[84]. Recognition of the effects of bioenergy expansion on surrounding systems (agriculture, industrial, and other) made consequential LCAs more common in recent years. These analyse bioenergy systems in the context of economic interactions; chains of cause and effect of bioenergy production and use; and effects of policies/other initiatives inducing the bioenergy increase. One important part of consequential LCAs is to investigate systemic responses to the bioenergy expansion, e.g. how the food system changes if increasing volumes of cereals are used as biofuel feedstock, and how petroleum markets respond if increased biofuel production results in reduced petroleum demand. They should also ideally consider rebound effects, which in the case of bioenergy means that if increased production of solid, liquid, and gaseous biofuels leads to lower demand for fossil fuels, fossil fuel prices will become lower and as a consequence demand grows[85]. Similarly, co-product consideration in LCAs should ideally model displacement of an alternative product as a dynamic result of market interactions, rather than assuming a certain substitution effect based on the properties of the co-product or alternative product. Auxiliary tools such as economic equilibrium models are therefore, as a rule, used in consequential LCAs.

The choice of method for the allocation of impacts between main product and by-product(s) strongly affects the performance. Figure 14 exemplifies the wide range of results that can be obtained for one bioenergy production system (wheat ethanol in Sweden) by varying three different factors: the fuel combusted in the conversion process, the time horizon and the allocation method. The upper diagram of Figure 14 shows the ratio of ethanol produced to external energy invested in the process and the lower one presents the net GHG emissions, including a comparison with gasoline. Results are given for allocation by economic value, by energy value, and 'system expansion' where the avoided impacts of a substitute product that the by-product replaces are accounted for. If by-products are utilised efficiently so as to maximise their energy and climate benefits, the performance of the bioenergy system improves substantially. However, economic realities may lead to uses that contribute less to climate benefits. Note also that the use of by-products as animal feed – which leads to great GHG reductions in Figure 14 when the by-product is assumed to replace soy protein imports in the system expansion method – is limited by the relatively small size of this by-product market, corresponding to a few percent of the transport fuel demand.

The indicators used in Figure 14 provide important, but not complete, information about the possible contribution of one specific bioenergy system to climate change mitigation. Different limiting resources may define the extent to which land management and biomass fuels can contribute to climate change mitigation, making different indicators relevant in different situations.[86]

- The *displacement factor* describes the reduction in GHG emissions that is obtained when bioenergy displaces another energy system. The GHG emissions reduction is expressed in terms of CO_2^{eq} and the displacement factor is then calculated as the amount of C in CO_2^{eq} reduction per amount of C in the biomass feedstock used. If the priority is oil dependency reduction, the displacement factor may instead be calculated as reduction in oil use per unit of biomass used. The displacement efficiency indicator does not take costs into account and it only discourages fossil inputs in the bioenergy chain if these inputs reduce the displacement efficiency.
- The indicator *relative GHG savings* (%, with respect to the fossil alternative – transport fuel, heat, electricity, or combined heat and electricity) favours biomass options with low GHG emissions. The metrics used in Figure 16 allow the calculation of relative GHG savings for specific substitution

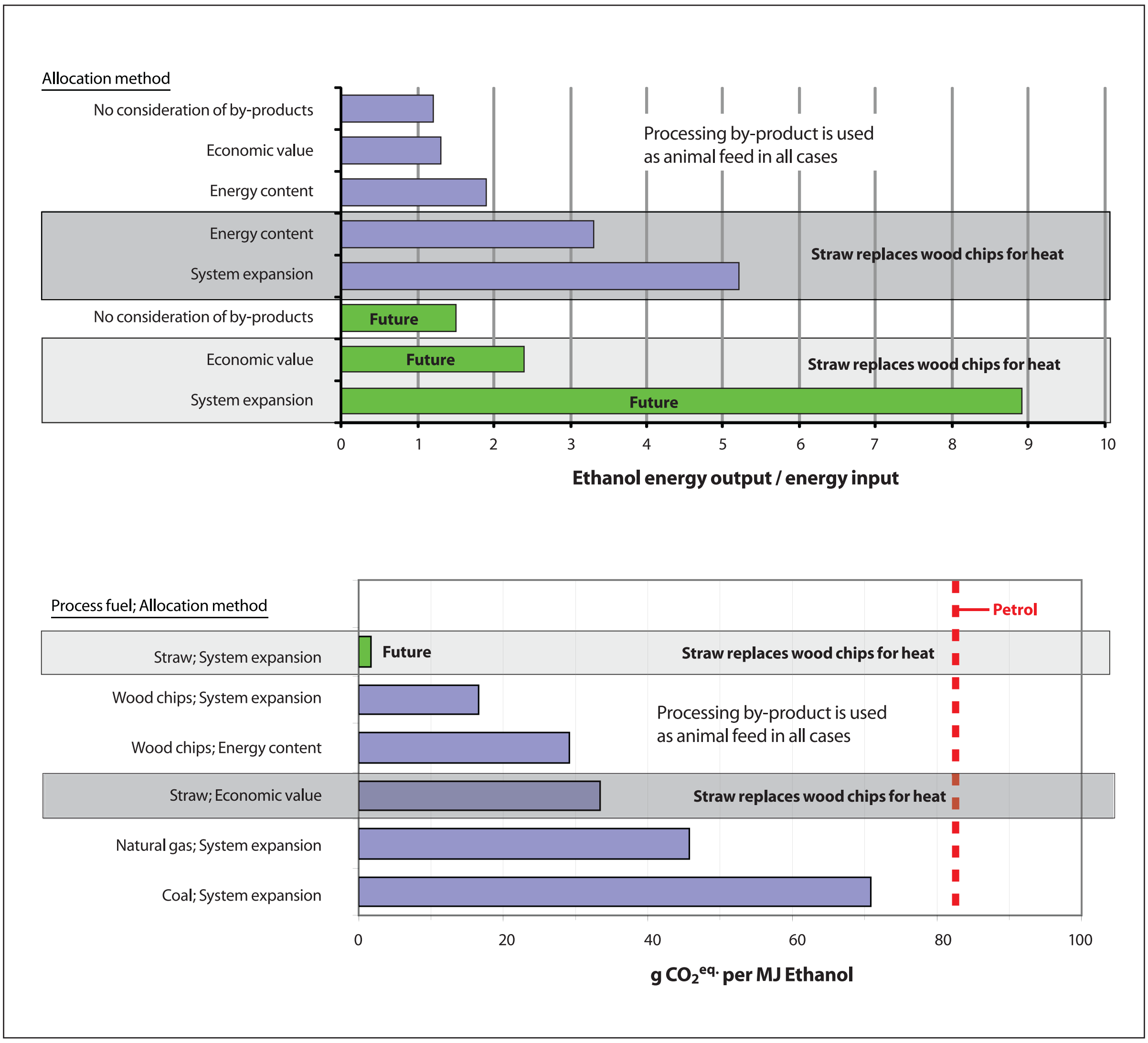


Figure 14. *Energy balances (upper diagram) and GHG emissions (lower diagram) for wheat-based ethanol production, taking into account various methods for considering by-product uses. System expansion refers to the assumption that the use of by-products leads to reduced production of an alternative product with the same use. The bars designated 'Future' show how the systems can improve due to development in both the feedstock production and the conversion to ethanol*[87].

patterns. This indicator ignores the amount of biomass, land or money required, and it can be distorted since each use can have different reference systems.

- The indicator GHG *savings per ha of land* favours biomass yield and conversion efficiency but ignores costs. Greater GHG emissions from production (e.g. due to employing irrigation or higher fertiliser input) improve the indicator value if the yield response is sufficiently good. In situations where water is the limiting factor rather than land GHG savings per m^3 of water can be a more relevant indicator.
- The indicator GHG *savings per unit monetary input* tends to favour presently available lowest cost bioenergy options. Strict prioritisation based on this indicator risks leading to failure in bringing bioenergy options to the market that have higher costs than the cheapest options in the near-term but are expected to be more cost-effective in the longer-term.

All the above indicators apart from *relative GHG savings* allow comparison of biomass use for the production of different types of energy carriers (electricity, heat, solid/fluid biofuels).

Furthermore, it is important to note that comparisons of individual options fail to consider the systemic aspects of different biomass uses. The individual biomass options that show the highest substitution benefit (as indicated by the indicators described above) do not necessarily represent the best uses of biomass for GHG mitigation. This depends on how demand for various energy services develops and also on the availability and cost of other competing low-C options.

Studies that compare specific bioenergy options with other energy options therefore 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 where integrated modelling can provide insights relates to the question whether biomass is most cost-effectively used for climate change mitigation in the transport sector or for producing heat and power. Studies using global energy system models have reported contrasting results and it has been shown that this is due to different modelling of how carbon emission reduction targets are implemented and of how low-carbon transport options other than biofuels develop over time[88]. In case other low-C options do not become available on a large-scale, biofuels may be the major option for climate change mitigation and energy security improvement in the transport sector. Future fossil fuels in the transport sector may also yield higher GHG emissions and improve the case for biofuels. Transport fuels from less conventional oil resources and coal-based Fischer Tropsch diesel both have higher life cycle GHG emissions than the gasoline and diesel used today.

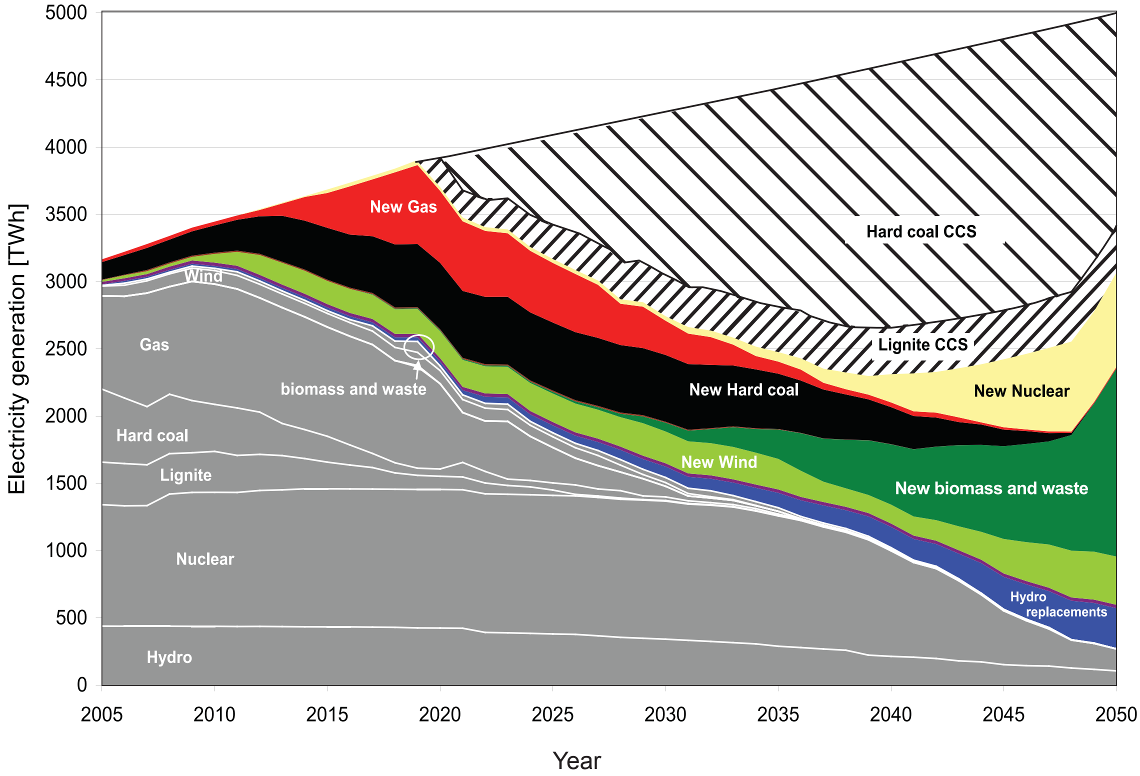
Similarly, future heat and power demand, as well as the availability of low-C options for stationary energy applications such as nuclear and fossil power employing CCS, also influences the demand for biomass in heat and power production when stringent GHG targets are established.

Illustrating this, Figure 15 shows modelled lowest cost technology pathways for the European power system under a CO_2 cap, and various assumptions about total electricity demand as well as availability and cost of bioenergy and other competing technology options. Two cases are shown in Figure 15 – a Base Case and an Efficiency-Renewables Case. CCS is in both cases assumed to become commercially available from 2020, and hence, prior to 2020 a fuel shift from coal to gas is observed in the Base Case to meet the CO_2 emission cap. This is less prominent in the Efficiency-Renewables Case that has a lower electricity demand (the CO_2 cap is the same). Part of the gas power expansion seen in the Base Case up to 2020 is configured as combined heat and power (CHP), which saturates the given heat demand. The Efficiency-Renewables Case uses less natural gas power (CHP), and thus employs biomass CHP at an earlier point than in the Base Case to meet the heat demand. Clearly, in a case where the CCS option would not become available on a substantial scale until some decades further into the future, biomass demand would likely increase substantially – especially in situations where nuclear and natural gas are considered problematic from security and import dependency points of view.

Another case where integrated modelling can provide support concerns 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 section 'Bioenergy and LUC in the Context of Global Climate Targets'.

GHG Emissions Reduction in the Absence of LUC

Figure 16 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 involves many uncertainties and the ranges presented in Figure 16 do not contain the total variation presented in the literature (an updated diagram based on an extended assessment is presented in the forthcoming IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation[90]). Meta-analyses aiming at providing synthesis conclusions face the challenges of assessing and comparing studies of a multitude of existing and evolving bioenergy sources employing different physical, chemical and biological conversion processes, and diverse feedstock production systems that are subject to variability in site specific environmental conditions. In addition, variations in results can also be due to methodology differences, and differences in the data used to characterise a given process can lead to very different mitigation benefit assessment for a particular bioenergy option[91]. For instance, reference and background electricity systems can be characterised based on using marginal or average electricity generation.



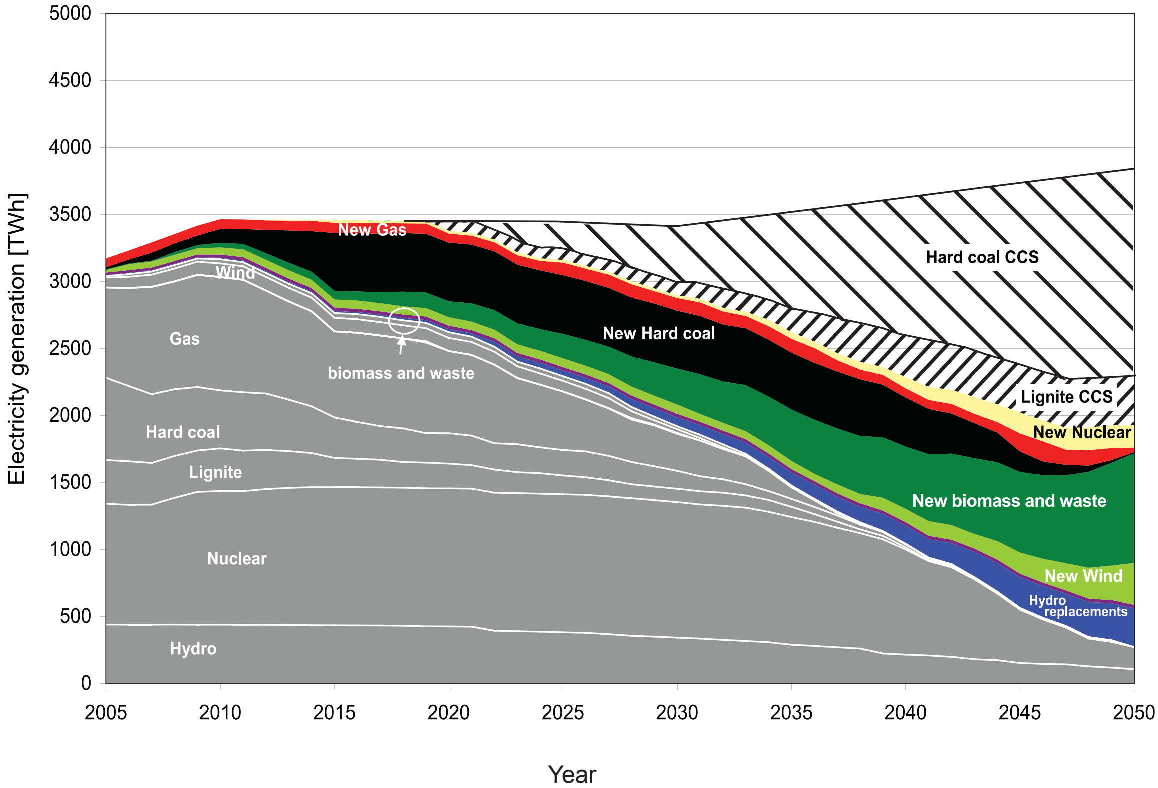


Figure 15. *Modelled electricity generation in EU-27 plus Norway for a Base Case (top) and an Efficiency-Renewables Case (bottom)*[89]. *The grey field in the lower part of the graphs represents the contribution to electricity generation from the present system where the fuel mix is indicated by white lines. To illustrate the size of modelled biomass demand: 1000 TWh of electricity requires about 9 EJ of biomass at 40% electricity generation efficiency. This can be compared to the energy content of the total EU25 industrial roundwood production at about 6 EJ yr^{-1}, and EU25 total cereals harvest at 4-5 EJ yr^{-1}. Producing 9 EJ of biomass would require that about 180 Mha, or 25% of the total agriculture area in EU27, be used for bioenergy plantations yielding 10 dry tons ha^{-1}yr^{-1}.*

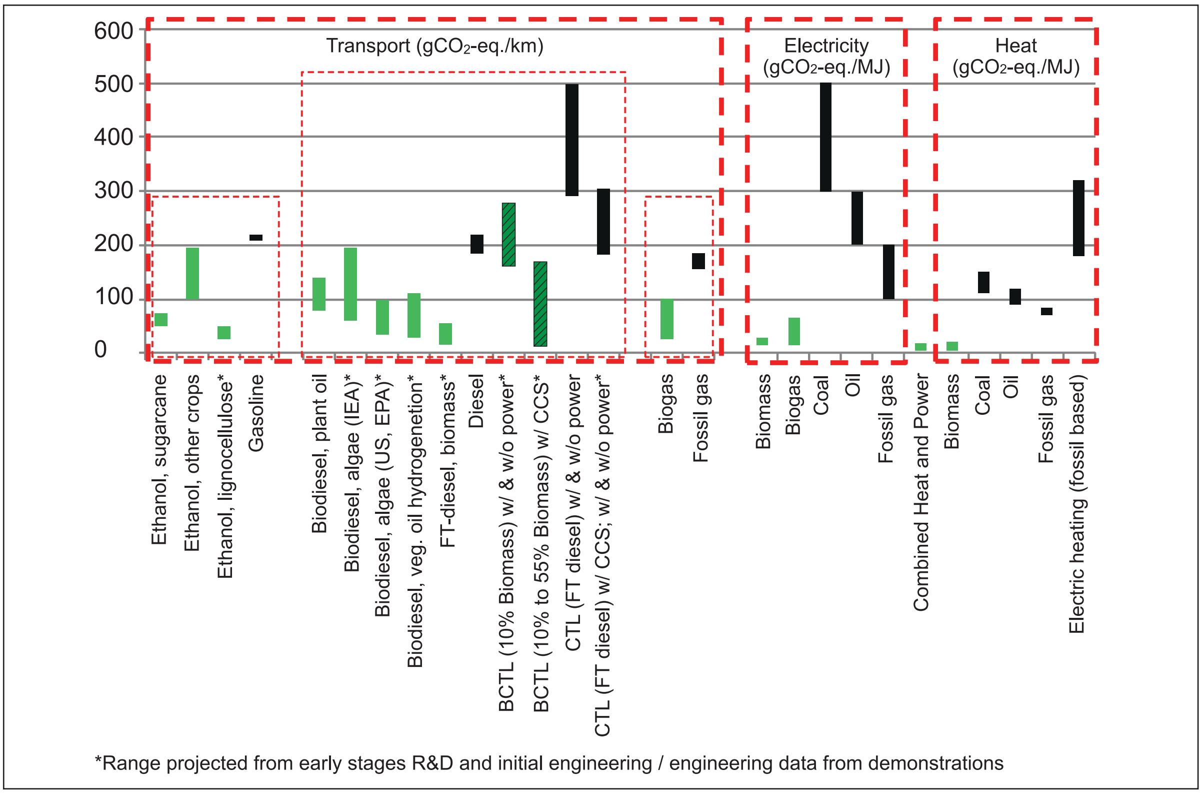


Figure 16. *GHG emissions (CO_2-eq.) per unit of output – km transport or MJ electricity/heat delivered to final end use – for a range of bioenergy (green) and fossil (black) options. Ranges reflect variations in performance as reported in the literature. Possible LUC emissions are not included here. '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 black/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[92].*

Due to the uncertainties and variations in conditions, review studies report varying estimates of GHG emissions and a wide range of results have been reported for the same bioenergy options, even when temporal and spatial considerations are the same[93]. Nevertheless, despite all uncertainties several conclusions can be drawn.

Generally, bioenergy will be most effective for GHG mitigation when it is adopted in association with other products i.e. by utilising biomass wastes of primary product chains, or biomass that has already served one or more functions. There are biofuel uses in the stationary energy system that lead to rather low mitigation benefits, such as if bio-electricity generated in an inefficient condensing plant were to replace new gas-based electricity, but in general, substitution of fossil fuels – especially coal – in heat and electricity generation provides greater and less costly GHG emissions reduction per unit of biomass than substituting biofuels for gasoline or diesel in transport. The major reasons for this are (i) the lower conversion efficiency, compared to the fossil alternative, when biomass is processed into biofuels and used for transport; and (ii) the higher energy inputs in the production and conversion of biomass into such fuels, when based on conventional arable crops. In certain cases, such as when landfill methane is used or biogas is produced from animal dung, very large mitigation benefits can be reached since direct methane emissions to the atmosphere are avoided.

However, as discussed above the stationary bioenergy sector can rely on a range of different low C 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 due to the inertia of vehicle stock turnover. Bio-electricity powered electric vehicles can offer higher mileage and GHG emissions reduction per unit of biomass than when liquid biofuels such as ethanol are used in a conventional internal combustion engine[94]. However, the difference mainly lies in the higher efficiency of electric vehicle propulsion, and biofuels can also be used in hybrid cars and plug-in hybrids. Thus, the electric drive train necessary for electric vehicles to become commercially viable will also substantially improve efficiency for these options. Whether bio-electricity or gaseous/liquid biofuels will be the preferred option for biomass-based personal transport in the longer-term will depend on a range of aspects, including – and not least – economic factors. Electricity might have a more difficult situation competing with liquid fuels as a preferred option for heavy vehicles, long-distance road transport, and sea and air transport.

It can also be concluded from Figure 16 that, contrary to some negative reports, biofuels 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 for reaching high GHG savings. As shown in Figure 16 future fossil fuels in the transport sector may also yield higher GHG emissions, and improve the case for biofuels. Transport fuels from less conventional oil resources and coal-based Fischer Tropsch diesel both have higher life cycle GHG emissions than the gasoline and diesel used today, especially in plants that do not employ CCS.

The question whether to use biomass for transport or stationary energy purposes may become less relevant in the longer-term, when bioenergy systems may increasingly consist of biorefinery technologies that produce liquid/gaseous biofuels for transport in combination with power, heat, solid biofuels, chemicals and other products. The driving factors in such applications are the synergies available with the higher total energy efficiency and resource efficiency obtained by combined approaches, and the potential added value from producing a range of products.

The choice of fuel for the feedstock-to-biofuel conversion process is critical for the GHG outcome and the use of coal in particular can drastically reduce the climate benefit of bioenergy. 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. As an illustration of this, GHG emissions for USA corn ethanol can vary significantly – estimates found a 3% increase compared to gasoline if coal is the process fuel and a 52% reduction if wood chips are used[95]. Analyses using updated values for crop management and yields, conversion process configuration, and by-product utilisation found emissions reductions of roughly 50-60% for maize ethanol in the USA[96]. Similarly, the low fossil GHG emissions reported for Swedish cereal ethanol plants are explained by the fact that biomass-based process energy is used[97]. In a third example, sugarcane ethanol plants that use the fibrous conversion process by-product bagasse as process fuel can provide for their own heat, steam and electricity needs and export surplus electricity to the grid[98]. Further GHG savings become possible as mechanical harvesting becomes established practice; while some of the harvest residues should be left on the field to conserve soil productivity a significant part can be used for energy.

However, the marginal benefit of shifting to use of 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. In addition, the GHG reduction per unit of 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 16 that solid, liquid, and gaseous biofuels can indeed be produced in ways that lead to significant net GHG emissions but they can still generate relatively high GHG savings if they replace very C-intensive fossil options. For instance, large GHG savings will likely be recorded when electricity from solid biofuels replaces electricity generated in an inefficient coal-based power plant – even in the instance where the production and transport of the solid biofuel to a power plant leads to significant GHG emissions. This underlines the importance that evaluations use several different indicators, including biofuel output per unit of biomass, land and water, cost per unit of GHG avoided, and GHG emissions per unit of energy service (which is used in Figure 16).

Finally, it can be noted that, in general, lignocellulosic options seem to offer the highest GHG emissions reduction regardless of whether the biomass is used for heat and power or for transport. In addition to the possibility of using lignocellulosic residues that cause few emissions, the cultivation of lignocellulosic crops (both herbaceous and woody) generally requires fewer agronomic inputs than conventional food/feed crops, which has a positive effect on GHG emissions (and overall environmental performance). As described earlier, some lignocellulosic crops can also be cultivated on lands not suitable for conventional food/feed crops and can enhance the mitigation benefit by sequestering C into soils and living biomass when grown on C-depleted soils.

However, it needs to be said that lignocellulosic transport biofuel options are not yet commercially available and the currently available so-called 1st generation biofuels will therefore continue to dominate for a number of years. Furthermore, currently available biofuels could also benefit from the commercialisation of technologies for converting lignocellulose to biofuels: the biofuel conversion of their fibrous by-products along with the conventional feedstock could improve their land use efficiency and GHG reduction potential.

GHG Emissions Reduction in the Presence of LUC

LUC can affect GHG emissions in a number of ways, including: (i) when biomass is burned in the field during land clearing; (ii) when the land management practice changes so that the carbon stocks in soils and vegetation change and/or non-CO_2 emissions (N_2O, NH_4) change; and (iii) when LUC results in changes in rates of carbon sequestration, i.e. the CO_2 assimilation of the land may increase or decrease relative to the case in which LUC is absent.

The significance of LUC (including changes in forest management) in GHG balances of bioenergy systems was demonstrated in the 1990s[99] when dLUC effects were also considered in LCAs of bioenergy systems[100]. Some studies also stressed the importance of considering indirect effects[101], but until now most studies have not considered iLUC. Standards currently being developed (e.g. CEN/TC 383 and ISO PC248) consider LUC, but while CEN/TC 383 only considers dLUC it is not yet decided whether – and if so how – to consider iLUC. The fact that bioenergy can have direct/indirect positive/negative effects on biospheric carbon stocks has been noted in the context of the United Nations Framework Convention on Climate Change – in particular the Clean Development Mechanism (CDM) projects concerned with land use, land use change and forestry (LULUCF) – and it has been proposed that sinks crediting under the CDM could stimulate bioenergy systems with a positive carbon sink function[102].

Recent modelling of LUC emissions: In recent years, risks from the negative impacts of LUC have been re-emphasised. A large number of studies have been carried out, many of which were initiated as a consequence of the debate generated by two studies published in Science in 2008[103]. Studies so far have published estimates of LUC emissions associated with, primarily, biofuels for transport.

Indicators such as *Carbon debt*[104] and *Ecosystem carbon payback time*[105] have been used to assess the importance of upfront LUC emissions arising from the conversion of land to bioenergy production. The basic idea of these indicators is to express the upfront LUC emissions in terms of years required until these initial GHG emissions have been fully compensated for by the annual GHG savings obtained when the biofuels are produced and used instead of fossil fuels. Other indicators, such as *Cumulative warming impacts* or *Global warming potential*, have been used to describe the dynamic effect of GHG emissions and discuss emissions timing and balancing between short and long-term climate benefits of bioenergy projects[106]. During these recent years, there appears to have been limited connection with earlier research in the area of LULUCF that partly address similar concerns, e.g. direct environmental and socio-economic impacts, and leakage[107].

Using the indicator *Ecosystem carbon payback time*, Figure 17 illustrates the importance of up-front LUC emissions for selected cases of land conversion to biofuel feedstock cultivation. In this case only dLUC emissions are included and additional iLUC emissions might take place in situations where other production is displaced when biofuel feedstock plantations become established (Figure 11). The left diagram shows payback times assuming current average yields and that set conversion efficiencies stay constant over time – possible improvements over time are not considered. The right diagram shows the payback times when the time-averaged yield (averaged over the total payback period) is set equal to the current top 10% of area-weighted yields. The conversion efficiencies are also kept constant in this case.

The payback times in Figure 17 are calculated based on some simplifications:

- The GHG emissions associated with production and distribution of transport fuels has not been considered. Since these currently tend to be higher for biofuels than for gasoline and diesel, this means that payback times are underestimated.
- The GHG savings from gasoline/diesel displacement has been set constant over time. Higher GHG savings, i.e. shorter payback times, would be achieved if biofuels conversion efficiency improved or more C-intensive transport fuels were replaced.

Increasing yields would further reduce payback times, but may require higher agronomic inputs leading to increased GHG emissions, notably N_2O. The payback times would increase if the feedstock production resulted in land degradation over time, impacting yield levels or requiring increased input to maintain yield levels.

As shown in Figure 17, all biofuel options have significant payback times when dense forests are converted into biofuel feedstock plantations. The starred points represent very long payback times for oil palm establishment on tropical peatland forests because drainage leads to oxidation of the peat material and causes CO_2 emissions over several decades, which can be several times higher than the displaced emissions of fossil diesel[108]. Under natural conditions tropical peatlands have negligible CO_2 emissions and small methane emissions[109]. Payback times can also be long when ecosystems containing less C are converted to feedstock cultivation if the associated biofuel production and use generates little GHG savings (e.g. soybean and castor in Figure 17).

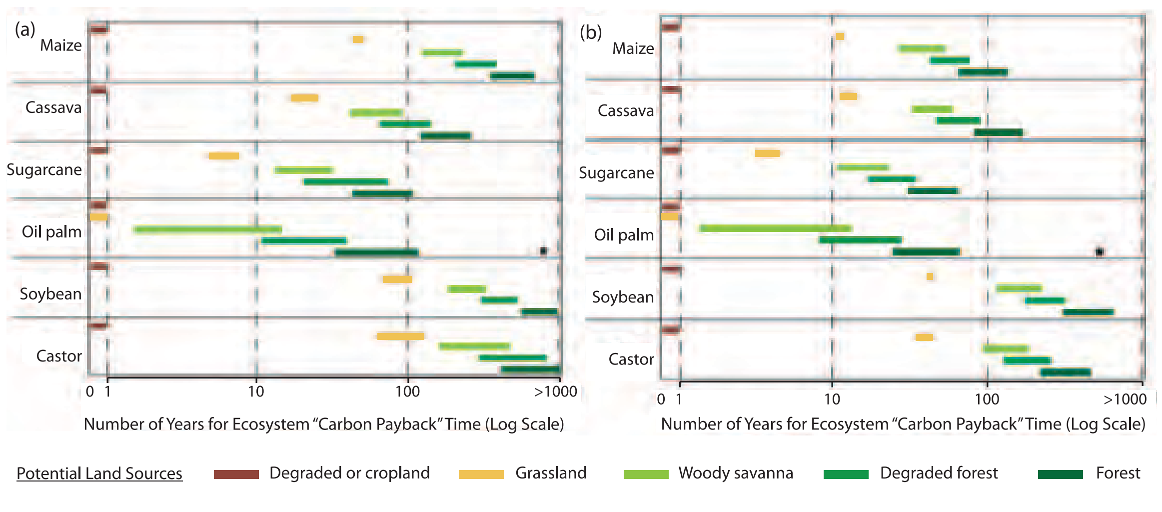


Figure 17. *The ecosystem carbon payback time for potential biofuel crop expansion pathways across the tropics comparing the year 2000 agricultural system (a) with a higher yield case (b). See text for further description of the two cases shown[105].*

In contrast to these cases, payback times are practically zero when degraded land or cropland is used for biofuel feedstock cultivation, and they are relatively low for the most productive systems when grasslands and woody savannahs are used (not considering the iLUC that can arise if these lands are used, e.g. for grazing). The targeting of unused marginal and degraded lands can thus be one option for mitigating dLUC emissions and for some options (e.g. perennial grasses, woody plants, mechanically harvested sugarcane) net gains of soil and above ground carbon can be obtained when land with relatively low C content is converted[110]. This is further discussed in the section 'Options for Mitigation LUC Associated with Bioenergy'.

The quantification of GHG emissions or CO_2 assimilation associated with LUC is subject to many uncertainties and there is variation in the amount of C stored in different ecosystem types (as illustrated by the bars in Figure 17). When the amount of C in soils and above ground biomass is accurately known for both pre- and post-conversion states it can be straightforward to calculate the GHG effects of dLUC for specific bioenergy projects. However, 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 intervals, and the use of fertilisers to increase growth). This is further discussed in the section 'Forest Management and Associated Carbon Flows'.

The inclusion of iLUC in quantifications of LUC effects adds greatly to the uncertainty. Causes of deforestation and other LUCs are diverse 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. Figure 18 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 shown in Figure 18 are illustrative of the complexities and uncertainties inherent in LUC analyses.

The assumed/modelled displacement effects of process co-products used as feed can have strong influence on LUC values. For European biofuels, if biofuel process co-products on the feed market displace soy meal and cereals, the net land area required to produce biofuel from EU cereal, rapeseed and sugar beet is estimated to become much lower than the gross land requirement (e.g. only 6% of gross land requirements for ethanol from feed wheat in NW Europe[112]). Large improvements in net GHG savings for European cereal ethanol and rapeseed biodiesel have also been proposed based on the fact that co-products displace imported soy as animal feed, which leads to reduced deforestation and other LUC for soy cultivation in Brazil[113].

This is also seen in Figure 18, where the contrasting results for corn ethanol and rapeseed biodiesel illustrate how the modelling of these links between the biofuel and food systems is crucial for the outcome. Negative LUC emissions were obtained for one study in Figure 18 due to the assumption that biofuel processing by-products would displace imported Brazilian soy as animal feed, indirectly reducing deforestation emissions. In the other studies included in Figure 18 this link between by-product uses 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

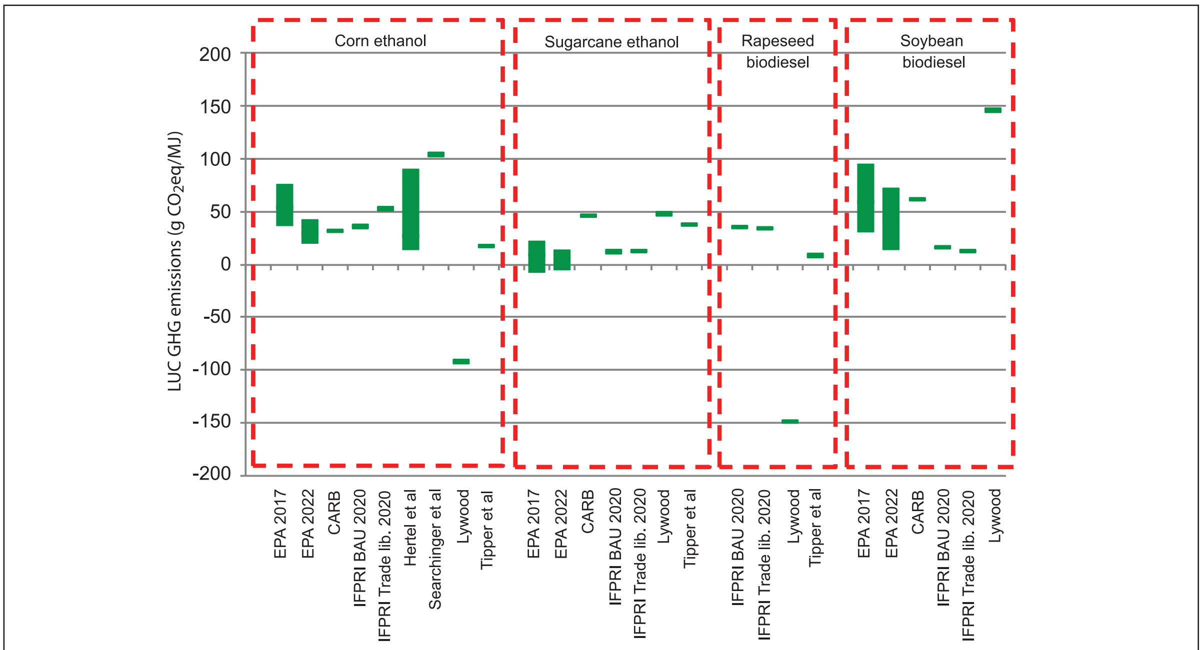


Figure 18. *Ranges of model-based quantifications of LUC emissions associated with the expansion of selected biofuel/crop combinations. The studies are reported with LUC emissions amortised over 30 years of production for comparison[111].*

induced increased soy cultivation in other countries such as Brazil, partly leading to increased deforestation as soy cultivation expands[114]. The marginal displacement effects of co-products may have a saturation level, although new uses may be developed, e.g. to produce more biofuels[115]. In this context, it is important to note that trade assumptions are critical and different for the various models.

Edwards *et al.* (2010)[122] compared how six equilibrium or partial equilibrium models quantified LUC in different world regions associated with a standardised marginal increase in demand for 1st generation ethanol or biodiesel. All models showed significant LUC with variations between models in both size and distribution over regions and crops (see upper part of Table 3). Note that the LUC emissions shown in the upper part of Table 3 are not model outputs: the different models were used to quantify land expansion and the LUC rates were just converted to corresponding LUC emissions assuming an average emission rate at 40 ton C ha^{-1} and a 30 year accounting framework.

Complementary to the ranges for the studies included in Figure 18, mid-range values from selected studies of LUC emissions for major biofuel crops are shown in the lower part of Table 3. Varying data resolution and differences in methodological approaches partly explain why studies report different LUC emissions. For instance, EPA (2010)[92] used economic equilibrium modelling and relatively high resolution of land use distribution[116] for Brazil and estimated mid range LUC emissions to be 5-10 g CO_2^{eq} MJ^{-1} for sugarcane ethanol. Other studies reviewed, that used similar modelling approaches, obtained 8 and 12 g CO_2^{eq} MJ^{-1} [117, 118]. Challenging the view that sugarcane ethanol in Brazil has relatively low LUC emissions, quantifications based on spatially explicit modelling point to relatively small dLUC emissions but iLUC emissions at a level that would extend the payback time for sugarcane ethanol by an additional 40 years[119]. Complementary to the values reported for USA maize ethanol in Figure 18 and Table 3, quantifications considering various probability distrbution to model parametres found ranges of 21 to 142 g CO_2^{eq} MJ−1 (95% central interval)[120] and 50 to 250 g CO_2e/MJ (Monte Carlo simulation)[121].

Illustrative of differences between models, and how changes shaping land use and the world economy at large influence LUC effects of biofuel production, Tyner *et al.* (2010)[124] report results from a set of simulations using the Global Trade Analysis Project (GTAP) model and also compare the results with the LUC emissions reported in Searchinger *et al.* (2008)[147], which is one of the Science papers stimulating the debate in recent years. In a first group of simulations – where growth in USA corn ethanol production takes place in the absence of other changes (base year: 2001) – the LUC emissions associated with increasing USA corn ethanol production were about 20% of the emissions reported by Searchinger *et al.* (2008). In a second group of simulations – taking into account changes in the world economy up to 2006 – the LUC emissions associated with modelled USA corn ethanol increases up to 2015 were about 16.6% of the Searchinger *et al.* (2008) level. Incorporating all economic, demographic and yield growth in a third group of simulations lowers the LUC emissions further to about 13.6% of the Searchinger *et al.* (2008) level. In another illustration of dynamic effects, Hertel *et al.* (2010)[125] found that market-mediated responses and by-products use moderated increases in cultivated land associated with USA corn ethanol to be just two-fifths of the amount estimated by Searchinger *et al.* (2008). The resulting iLUC emissions were estimated to be about 75% lower (Figure 19).

Examples of alternative methodological approaches to iLUC, associated with USA biofuel production, include Kim and Dale (2011)[126] who used a bottom-up, statistical approach and found that biofuel production in the USA from 2002 to 2007 was not significantly correlated with changes in croplands for corn (coarse grain) plus soybean in regions of the world which are corn and soybean trading partners of the USA. They concluded that either their empirical approach was not capable of detecting iLUC from USA biofuel through 2007, or this biofuel production did not induce iLUC – i.e. crop intensification absorbed the effects of expanding biofuels production. They called for more sophisticated methodologies to detect iLUC from empirical data. Reaching similar conclusions, Oladosu *et al.* (2011)[127] made a systematic decomposition analysis of the empirical data from 2001 to 2009 and found little support for large land use changes or diversion of corn exports because of ethanol production in the USA during the past decade.

Table 3. LUC results produced by different economic models for marginal increases in biofuel production from different feedstocks.

Biofuel system	LUC emissions *(g CO_2^{eq} MJ^{-1})*
Modelling of LUC effects of marginal biofuel demand increase[122]	*Calculated from modelled LUC effect assuming average LUC emissions at 40 ton C ha^{-1} and 30 year accounting framework*
EU ethanol	26-87
EU biodiesel	28-225
USA ethanol	12-101
Survey of studies[123]	*Mid range values and 30-year accounting framework*
USA maize ethanol	14-85 (higher resolution models); 100 (earlier model)
Sugarcane ethanol	5-12
EU wheat ethanol	18-45
Soy biodiesel	40-63
Rapeseed biodiesel	35-45

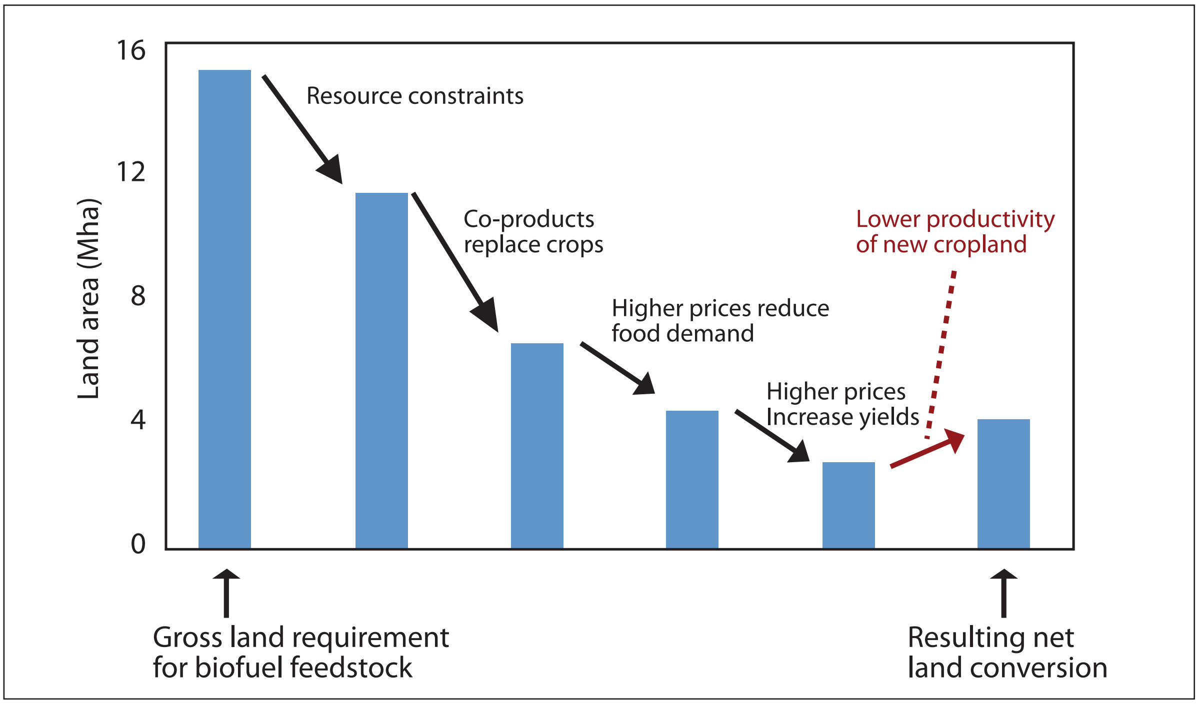


Figure 19. *Illustration of how market-mediated responses reduce the LUC effects of biofuel expansion. Reproduction of Figure 2 in Hertel et al. (2010)[125]. The term 'Resource constraints' represents the fact that production factors (land, labour, capital) are not in perfect elastic supply and that finite availability of suitable land induces a price response resulting in more intensive livestock and forestry production and also reduced demand for non-food products (food demand is reduced later in the 'response chain' shown in the figure).*

The relative contributions of changes in yield and land area to increased crop output are, together with assumptions about trade, found to be critical factors in model-based LUC estimates[128]. Approaches to set yield levels on new cropland versus existing cropland can be rather simplistic. For instance, in the GTAP model the approach was recently updated to provide these yield levels from a process-based biogeochemistry model along with spatially referenced information on climate, elevation, soils, and vegetation land use data. Earlier it was simply assumed that productivity of one unit of new croplands is equal to two-thirds of the productivity of one unit of existing croplands, all across the world[124].

Edwards *et al.* (2010)[122] state that the marginal area requirement per extra unit output of a particular biofuel should increase as total biofuel production increases, due to decreasing productivity of additional land converted to biofuel feedstock production. Lywood *et al.* (2009)[111], however, state that the extent to which output change is met by yield or land area change varies considerably between crops and regions, and that there is no evidence that average yields decline as more land is used in the cases of EU cereals and USA maize[129]. They estimate that yield growth contributed 78% and 58% of incremental output growth for EU cereals and USA maize, respectively, during the period 1961-2007. Conversely, area expansion contributed to more than 60% of output growth for EU rape seed, Brazilian sugarcane, South American soy, and oil palm in South East Asia.

Given the variation among regions, it is obvious that the conditions for international bioenergy trade will influence the relative contribution of yield growth versus cropland expansion to increased biofuel production, since trade prospects influence where in the world the additional biofuel will be produced when demand increases in a given country. Biodiesel is an illustration – the oil yield per hectare is several times larger for oil palm compared to alternatives such as soybean, sunflower and rapeseed. The land use consequences of increased biodiesel demand in, for example, Germany therefore differ greatly depending on whether there are any import restrictions on oil palm biodiesel. As illustrated by Figure 17, the consequences for LUC emissions can also differ greatly depending on what type of vegetable oil is produced and where. The interconnections with the food sector further complicate matters.

There is also a difference in how increased production of different biofuels translates into demand for new biofuel feedstock plantations. Ethanol production facilities that use cereals can use feedstocks from quite long distances, while increased production of sugarcane ethanol will, to a large extent, be accomplished based on construction of greenfield ethanol mills and establishment of sugarcane plantations in the vicinity of these new mills. Trade conditions are also relevant here. For instance, biofuel producers in countries that have import taxes on biofuels may benefit from using imported feedstocks unless there is also an import tax on the feedstock. International trade may also take place for processed feedstocks; vegetable oils have long been traded internationally in the food industry.

There is a weak empirical basis for deriving price-yield relationships[130] and the yield levels will be determined by a complex set of more or less interrelated factors rather than by basic crop prices – which makes model calibration difficult. Using Brazilian sugarcane as an example[¥], at present (2011) Brazilian ethanol exports to the EU are down to a low level and to a large extent have been displaced by subsidised corn ethanol that has become in surplus in the USA due to the 2008 financial crisis. The financial crisis also caught the Brazilian sugarcane sector with a high debt situation due to large investments in the construction of new mills and expansion of existing ones. The mills could not find money to run the plants during the crushing season and had to sell stocks of ethanol and sugar at very low prices, making things even worse. Furthermore, due to the shortage of money the mills had to reduce fertiliser and herbicide applications as well as the renewal of older cane fields, which will lead to lower yields for two or three subsequent crops. The weather in recent years has also played a role. Too much rain in the second half of 2009 reduced the cane sugar content and shortened the harvesting period; less cane was crushed and this cane contained less sugar than usual. 2010 was drier than the average and that has reduced the expectation of cane yields for the 2011 season.

The longer-term land use consequences of future ethanol expansion in Brazil will depend on several factors, including: (i) the outcome of the present revision of the Forest Act, which is the most important legal framework for regulating conservation and restoration on private land[131]; (ii) development of international mechanisms such as reducing emissions from deforestation and forest degradation (REDD) and various certification schemes, sustainability standards and other systems influencing land use (e.g. the Brazilian sugarcane agro-ecological zoning that was recently established to guide sugarcane expansion); and (iii) whether Brazil becomes successful in developing alternative expansion strategies for its agriculture, where it is especially important to stimulate productivity improvements in meat and diary production to make room for cropland expansion that does not require the conversion of forests and other natural ecosystems[119].

Of course, productivity development in agriculture and establishment of policies, legal systems, and other mechanisms to address concerns about LUC consequences influence future land use and LUC emissions in regions other than Brazil. This presents significant challenges for economic equilibrium modelling since incorporating effects of innovation in land use and policy can be difficult due to the lack of empirical historic data. Adding to the uncertainties, agriculture and forestry are likely to be significantly affected by climate change and this will shift the pattern of global comparative advantage in land use. The possible consequences of climate change for crop yields are not firmly established but indicate a net negative global impact, where damage will be concentrated in tropical developing countries that will lose agriculture production potential while the northern industrialised countries might gain[132].

To summarise, quantification of LUC and associated GHG emissions is a challenge for science and convergence of results towards substantially narrower ranges is unlikely in the near future[133]. Important aspects include geographical resolution of models, interactions between different parts of the biofuel-food-agriculture-forestry systems, and how these systems respond to changes in market and policy – including instruments to address concerns about deforestation and other LUC.

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 present bioenergy initiatives, in both positive and negative directions, and that iLUC emissions may in some instances cause the major part of the LUC emissions, implying that much of the LUC emissions may be caused by others rather than those investing in the bioenergy expansion. 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.

Bioenergy options that use lignocellulosic feedstocks are projected to have lower LUC emission values than those of 1st generation biofuels[134]. As noted above, some of these feedstock sources can be used without causing LUC. Lower LUC values might be expected for bioenergy plants that have high biofuel output because of high productivity, allow multiple products (e.g. animal feed), or can avoid competition for prime cropland by using more degraded or marginal lands, where the GHG reduction can be immediate (See the section 'Options for Mitigating LUC Associated with Bioenergy'). The lower productivity of such lands, however, results in higher land requirement per given biomass output, and presents particular challenges, e.g. in relation to water and biodiversity. Also, as many lignocellulosic plants are grown under longer rotations they should be less responsive to price increases, since the average yield over a plantation lifetime can only be influenced through agronomic means (notably increased fertiliser input) and by variety selection at the time of replanting. Thus, output growth in response to increasing demand is more readily obtained by area expansion for these multi-year rotation plantations.

As illustrated by the above overview, much of the recent attention to bioenergy and LUC has primarily been concerned with the question of whether bioenergy expansion in response to near-term targets will reduce net GHG emissions. Many studies have therefore considered rather small changes in energy and land use systems and investigated to what extent there is 'buffering capacity' in the food system that mitigates the LUC effect of near-term biofuel demand shocks. It needs to be noted that conclusions from such studies should not be generalised as being also valid for the case of more substantial transformation of energy and land use systems towards a longer-term situation where bioenergy would contribute a more significant part of global energy supply.

Integrated energy-industry-land use/cover models can give insights into how an expanding bioenergy sector interacts with others in society, influencing longer-term energy sector development, land use, management of biospheric C stocks, and global cumulative GHG emissions.

¥ *Personal communication, Manoel Regis Lima Verde Leal, CTBE - Bioethanol Technology Center, and Arnaldo Walter, Faculdade de Engenharia Mecanica – UNICAMP, Campinas University, Brazil.*

Among early examples, a model implementation of the LESS biomass intensive scenario, which was developed for IPCC SAR,[135] revealed that LUC emissions associated with bioenergy could significantly reduce the GHG savings of expanding bioenergy, and that the outcome was sensitive for regional emissions and feedback in the C cycle[136] This type of model-based study – some of which are presented in the next section – confirms the importance of certain mitigation options with regard to GHG emissions associated with bioenergy, such as increasing land use productivity while minimising N_2O emissions. They also indicate that conclusions based on evaluating individual bioenergy systems (especially within a short-term perspective) may not hold up to the test of evaluations using a broader perspective. This is discussed further in the section 'Bioenergy and LUC in the Context of Global Climate Targets' later in this report.

Influence of LUC on the GHG outcome of biofuel expansion strategies: While the above discussion has concentrated on the individual project level, Figure 20 illustrates LUC effects on a more strategic level by showing how LUC emissions can influence the net GHG reductions obtained by expanding the production of biofuels for transport (see Table 4 and the scenario description below). The quantifications shown in Figure 20 are based on a general equilibrium approach, modelling responses of consumers and producers to price changes induced by the competition of biofuel feedstock production with conventional uses (food, feed and fibre) of available resources. In addition to modelling LUC, this approach considers production intensification on existing agricultural land, use of biofuel by-products such as animal feed as an additional input into feed markets, as well as consumer responses to changing availability and prices of food commodities.

The LUC emissions shown in Figure 20 are due to the additional need for cultivated land compared to a baseline projection without any increase in the production of crop-based biofuels (which is kept constant at the 2008 level), thus, it is the sum of dLUC and iLUC emissions that is shown.

By 2030, additional land conversion due to increasing biofuel consumption amounts to 11 and 22 million ha for WEO and TAR respectively (i.e. additional land required to increase biofuel production from the baseline level up to the level in WEO and TAR). By 2050, 17.6 and 24.6 million ha of land has been converted to biofuels production. For comparison, around 1.6 billion ha of land are used for crop production, with nearly 1 billion ha cultivated in developing countries. During the last 30 years the world's crop area expanded by some five million ha per year, with Latin America alone accounting for 35% of this increase. The arable land expansion to meet growing future food and feed demand in the baseline scenario is around 120 million hectares by 2030 and 170 million hectares by 2050. Africa and Latin America account for the major part of total net arable land expansion. The new 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 and thus result in significant LUC emissions.

The 'land saving' effect of using biofuel conversion co-products as animal feed was found to be 5-8 million hectares for the biofuel scenarios, with around two-thirds of the effect in the developing world. Thus, if these co-products were not used as animal feed the GHG balance of biofuel consumption would worsen significantly due to additional land use conversions and associated GHG emissions, of which a large part would take the form of deforestation in Latin America.

The TAR scenario 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 benefits than the IEA/WEO 2008 reference scenario[138] 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 that are assumed to avoid deforestation, thus leading to lower LUC emissions and higher GHG savings from fossil fuel substitution (Figure 20). The higher deployment rate for 2nd generation biofuel technologies in TAR after 2020 sees little additional land put into cultivation compared to the baseline.

Figure 20 shows the accumulated GHG gains and losses for the two biofuel scenarios (WEO and TAR) and their variants with crop higher productivity growth (WEO-vP and TAR-vP). Cumulative net GHG savings are closely linked to the effects of arable land expansion and subsequent land use conversions. 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. As a

Table 4. Scenario assumptions. Fuel consumption given in Mtoe[137].

	Baseline		WEO		TAR	
	2020	2030	2020	2030	2020	2030
Developed Countries						
Final consumption of transport fuels			1505	1486	1505	1486
Share of biofuels in transport fuels			4.2%	5.4%	8%	12%
Share of 2nd generation			4%	19%	33%	51%
Developing Countries						
Final consumption of transport fuels			1174	1529	1174	1529
Share of biofuels in transport fuels			2.7%	3.0%	6%	8%
Share of 2nd generation			0%	4%	3%	19%

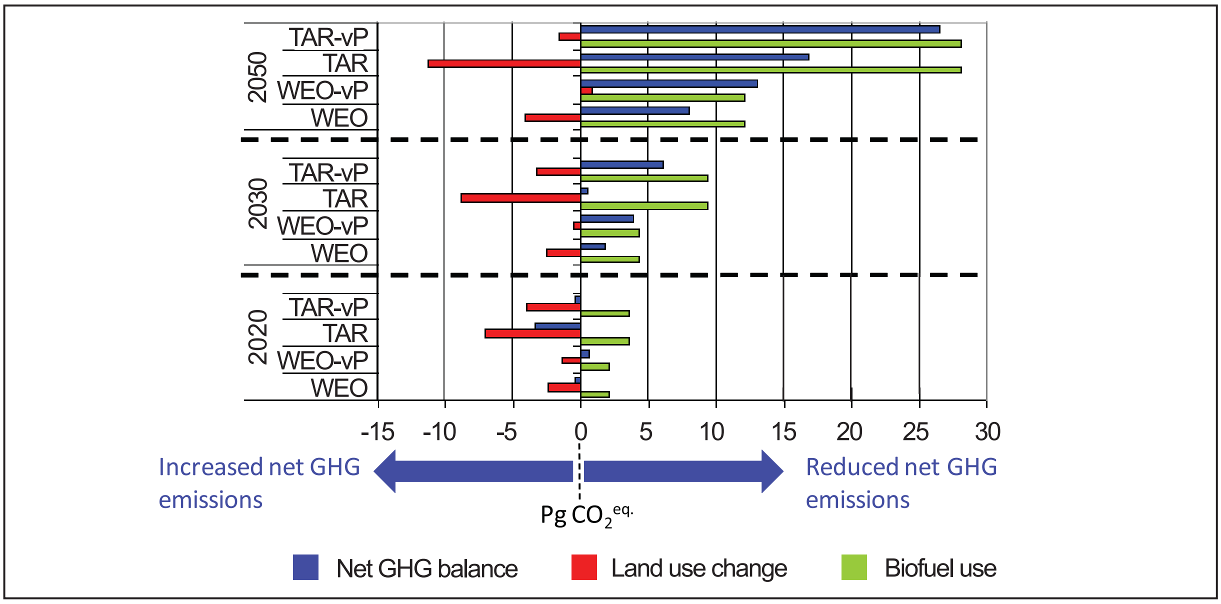


Figure 20. *Accumulated net GHG savings of biofuel scenarios[137]. The green 'Biofuel use' bars show GHG savings (positive) from biofuel replacement of gasoline and diesel; the red 'Land use change' bars show GHG emissions (negative) caused by LUC and iLUC; and the blue 'Net GHG balance' bars show the 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 and 2nd generation biofuels are gradually deployed after 2015. TAR has roughly twice as high biofuel use and faster deployment of 2nd generation biofuels. The vP scenarios have higher agricultural productivity growth in developing countries leading to lower LUC.*

consequence, GHG savings resulting from the replacement of fossil fuels with biofuels accumulate only gradually over time and net GHG balances do not become positive until after 2020 for WEO and TAR. 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 WEO and TAR.

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) resulting in less LUC in these scenarios, and consequently in higher net GHG reductions in these biofuel scenarios. For example by 2050 the scenarios WEO-vP and TAR-vP cause no additional deforestation compared to the reference scenario.

As discussed above, biofuels for transport can be motivated by several reasons and the strict requirement for almost immediate net GHG savings, implying practically zero LUC emissions, can be questioned, as is further elaborated in the section 'Bioenergy and LUC in the Context of Global Climate Targets'. 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. As has been shown, some alternatives such as sugarcane ethanol and lignocellulose ethanol are able to achieve a significant positive balance in short-term periods.

Also exploring the LUC and GHG consequences of expanding biofuel production in order to meet biofuel mandates and targets currently announced around the world, a recent World Bank study[139] that restricted the biofuel portfolio to include only 1st generation biofuels found large differences in cumulative net GHG savings depending on LUC patterns. If biofuel mandates and targets announced in more than 40 countries were realised by 2020, and if cropland expansion was limited to take place on only pasture land instead of taking place on both forests and pastures, the net increase in cumulative GHG emissions would cease by 2021 – one year after the assumed full implementation of the mandates and targets – instead of 2043, which was the case when both pastures and forests were converted to cropland.

Focusing instead on 2nd generation biofuels, Melillo *et al.* (2009)[140] quantified the GHG emissions associated with LUC from an expanded global cellulosic biofuels programme over the 21st century and found similar levels of cumulative GHG emissions to the earlier cited study of LUC associated with the IPCC SAR LESS biomass intensive scenario. The study concluded that (i) iLUC was a larger source of carbon loss than dLUC; (ii) fertiliser N_2O emissions was a substantial source of global warming; and (iii) forest protection and best practices for nitrogen fertiliser use could dramatically reduce emissions associated with biofuels production.

In another study analysing different policy options for limiting CO_2 concentrations to low levels Wise *et al* (2009)[141] found that the design of policy instruments – essentially including or not including LUC emissions in a C tax regime covering fossil C – can strongly influence the nature of bioenergy development and associated environmental consequences including the net GHG savings from bioenergy. Taxing LUC emissions lowered the cost of meeting environmental goals, but also induced rising food crop and livestock prices and expansion of unmanaged ecosystems and forests. The study stressed the importance of limiting terrestrial C emissions, and improved crop productivity was proposed as a potentially important means for GHG emissions reduction, with the caution that non-CO_2 emissions (not modelled) need to be considered.

As will be further discussed in the section 'Bioenergy and LUC in the Context of Global Climate Targets', deforestation for the purpose of bioenergy production may not always be undesirable from a strict climate and cost efficiency perspective. In some places a certain level of upfront LUC emissions may be acceptable in converting forest to highly productive bioenergy plantations due to the climate benefits of subsequent continued biofuel production and fossil fuel displacement. Illustrative of this, while C pricing as a sufficient mechanism to protect forests was proposed by Wise *et al.* (2009) and supported by others,[142] Persson and Azar (2010)[143] report that pricing LUC emissions could potentially make many of the current proximate causes of deforestation unprofitable (e.g. extensive cattle ranching, small-scale slash-and-burn agriculture and woodfuel use) but might not suffice to make deforestation for establishment of productive bioenergy production unprofitable. The reason is that higher C price will increase not only the cost of forest clearing but also the revenues from bioenergy production[144].

Forest management and associated carbon flows: As already noted, forest bioenergy projects can lead to changes in forest C stocks while not always being recorded as causing LUC (this depends on which definitions are used). The size and timing of forest C flows and C stock changes has also become a topic for debate as governments and other authorities try to ensure that forest bioenergy initiatives contribute positively to climate change mitigation[145]. In this context, critics do not question that long-rotation forest management with some level of biomass extraction for energy can be maintained on a sustainable basis. It is rather the climate change mitigation benefit that is questioned and diverging standpoints can, to a significant degree, be explained by opponents taking different perspectives on bioenergy and climate change mitigation.

There is no disagreement on a conceptual level – i.e. that the CO_2 emitted due to bioenergy use was earlier sequestered from the atmosphere and will be sequestered again if the bioenergy system is managed sustainably. The disagreement arises because emissions and sequestration are not necessarily in temporal balance with each other. The dynamics of terrestrial C stocks in long-rotation forestry – where the temporal imbalance of C dynamics differ substantially for the bioenergy use on the one hand and decomposition/re-growth processes in the forest ecosystem on the other hand – lead to GHG mitigation trade-offs between biomass extraction for energy use and the alternative of leaving the biomass as a carbon store that could further sequester more carbon over time[146]. Depending on the perspective taken – e.g. spatial scale (stand level vs. landscape level) and time scale (short vs. long-term) – different answers are obtained regarding the contribution of forest bioenergy to climate change mitigation.

It is also commonly agreed that harvested forest systems have the best climate change mitigation capacity in the longer-term. Even so, evaluations using shorter time horizons – for instance focusing on near-term GHG reduction targets – might find harvested forest systems providing bioenergy and other forest products less attractive than forests that are managed to maximise C sequestration. The CO_2 emissions arising from the conversion of forest biomass to a biofuel that is subsequently combusted are cancelled out by the CO_2 uptake in growing biomass but as these processes will take a much longer time the consequence might be (depending on the design of the accounting system) that forest bioenergy systems appear less favourable from a short-term climate change mitigation perspective. In even-aged stands subject to clear cutting, if much of the extracted biomass is used for bioenergy (or to produce other short-lived products), if the accounting period is set to start at the point of wood extraction, and if biomass left in the forests is assumed to have a slow decomposition rate (although decomposition rates can be quite high[147]), then biomass use for energy may be accounted as being worse than the fossil alternative in the short-term.

As an example of countries that have a considerable forest industry and where the traditional forest management is based on rotation forestry in even aged stands, Figure 21 shows how gross felling has varied in Sweden during the period 1853-2003. Rotation ages in Sweden range from about 130 years in the most northern region to about 90 years in the southern region*. Figure 21 also shows the annual increment in Swedish forests, which has roughly doubled during the period 1926-2003. During recent decades, forest wood fuel production

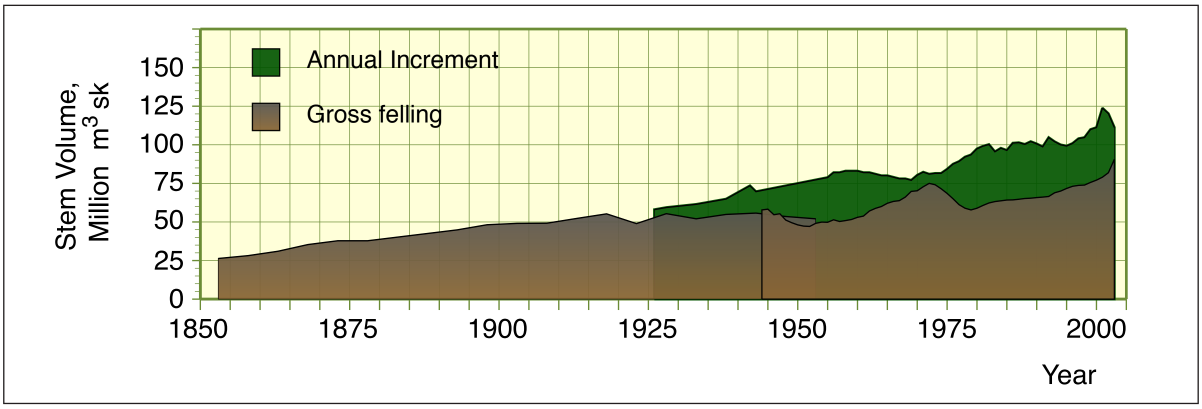


Figure 21. *Forest survey data showing annual increment 1926 – 2003 and gross felling 1853 – 2003 in Sweden[149]. Felling is shown in two series reflecting different methods of estimation. Cubic metres standing volume including stem volume over bark from stump to tip is denoted m³ sk.*

** One rotation in this context is known as the number of years from when the stand is established up to a mature age when all trees are harvested by felling and removal.*

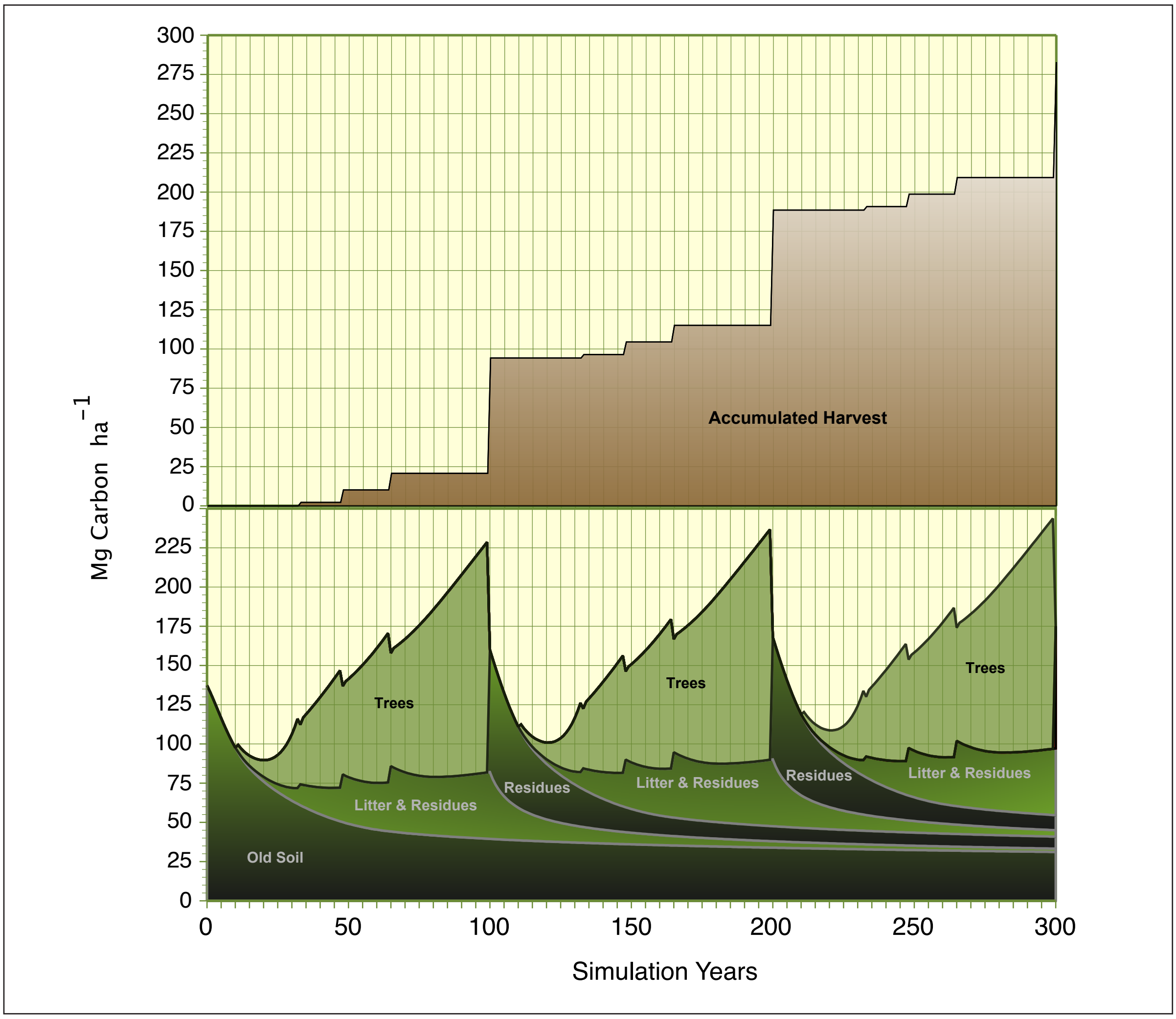


Figure 22. *Modelled C dynamics for a Norway Spruce forest stand in southern Sweden, including the C content in the accumulated harvest from the stand. The assumed management resembles the dominant management regime during the previous decades, i.e. only stem wood has been removed at harvests, and thinning has been done at intervals prescribed by the Swedish Forest Agency. The stand is thinned three times (year 33, 48 and 65, with biomass harvest corresponding to about one-fourth of the basal area) and final harvest takes place after 100 years where only stems are removed. It is assumed that 10% of the stem biomass is left as harvest residue (tops). SOC comes from litter fall from living trees and residuals left on site after harvests. The simulation period starts after a clear fell with only stem wood removal and extends 300 years into the future to cover three forest rotations*[151].

has increased considerably in Sweden while forest C stocks have increased, a fact sometimes used as an argument when responding to criticism of forest wood fuel systems as not contributing to climate change mitigation in the near-term[148].

Conventional forestry with long rotations in Sweden, where residues are utilised for energy, will be discussed below as an illustrative example showing how forest management can affect the associated C stocks and flows and how forest bioenergy systems contribute to climate change mitigation over varying time scales.

Figure 22 shows the modelled changes over time of C stocks in soils and above ground biomass for a Norway spruce stand in Southern Sweden subject to the practice that has dominated Swedish forestry during the recent decades, where harvest residues are left on the ground both after thinning and final felling[§]. The initial size of the 'old soil' C stock shown in Figure 22 is estimated based on average litter production and assuming that harvest residues are left on the ground at clear felling year 0, thus adding to the initial C stock. Modelling for spruce forests in northern Sweden resulted in a qualitatively similar picture, but with lower C stocks due to the lower site productivity. A second model was also used to simulate the same management regimes in the same forests and arrived at the same qualitative results[150].

As can be seen in Figure 22, the ecosystem C stocks at a stand level initially decrease when the remaining harvest residues decompose, since the new tree growth initially does not fully compensate for the C losses associated with residue decay. Forest sites with lower productivity require a longer time for recovery than a higher productivity site due to the slower tree regrowth. Figure 22 also shows the C content of the

[§] *The term thinning refers to recurrent selective harvesting of trees to maintain good health and high productivity of the stand.*

accumulated harvest. Depending on the use of the harvested biomass, this harvested C can be stored and kept away from the atmosphere for varying lengths of time. The net GHG consequences of forest wood harvest and use also depend on the displacement effect of this use, e.g. if wood initially is used for construction, displacing concrete in buildings, and later (after having served its initial purpose) is used as fuel, displacing coal, the GHG outcome is more favourable compared to a scenario where the wood first displaces less C intensive alternatives and later is just burned without energy recovery.

Changed forest management in response to bioenergy demand influences forest C flows and can lead to increased or decreased forest C stocks. Shortening forest rotation length in order to obtain increased output of timber and biomass fuels leads to decreased C stock in living biomass (other things being equal). Intensified biomass extraction in forests, for instance for bioenergy, can lead to a decrease in soil C or the dead wood C pool compared to existing practice. Conversely, if changed forest management employing intensified extraction also involves growth-enhancing measures, forest C stocks may increase. To the extent that increased demand for forest bioenergy makes such measures feasible (i.e. they would not have taken place in a scenario without bioenergy demand) the effects of changed forest management should be considered when evaluating the climate change mitigation benefit of forest bioenergy.

In one example, site preparation increases forest productivity by drastically shortening the regeneration phase, but may on the other hand lead to faster decomposition of soil organic matter[152]. In another example, fertilisation has long been a management option to increase forest production, and experiments show that stem volume production can, even in already highly productive forests, be more than doubled with optimal fertilisation and, when needed, irrigation[153]. This increased stem volume production should result in an approximately equal increase in litter production (although fine roots may not respond as much) and a similar long-term increase in soil carbon (Figure 23). It has also been shown that fertilisation slows down decomposition in forests contributing further to increasing soil carbon stocks[154]. Other recent studies of the possibilities to intensify forest management (particularly in the boreal forests) confirm that stand management can increase both the carbon stocks and the biomass and timber production on the same piece of land[155].

As stated earlier, tropical forest systems in particular appear to have significantly reduced capacity to reduce GWP as C sinks due to N_2O emissions. Estimates indicate, however, that increased N_2O emissions will not significantly counteract the GWP reduction associated with fertilisation-induced forest C stock increase in northern latitudes; N_2O emissions from increased fertiliser applications are estimated to amount to less than 2% of the corresponding increased carbon sequestration in Swedish forests[156].

It is not possible to assign a global general ranking of forest options based on their contribution to climate change mitigation. The climate benefit of a specific option is determined by many parametres that are site-specific and can differ substantially depending on forest management practice and the characteristics of the bioenergy system as well as the energy system displaced.

The relative merits of forest biomass extraction for bioenergy versus C sinks management are dependent on:

- The efficiency with which bioenergy can displace fossil-based energy. This efficiency is high if (i) the biomass is produced and converted efficiently; (ii) the biomass production and conversion causes few GHG emissions; (iii) a carbon intensive fossil fuel is displaced; and (iv) the replaced fossil fuel would have been used with low efficiency.
- The time period of consideration: the longer the time frame of the analysis, the more attractive bioenergy is in comparison with C sequestration, because the latter is constrained by saturation (only a limited amount of C can be stored on a hectare of land), whereas bioenergy can be produced repeatedly, from harvest cycle to harvest cycle.
- The growth rate of the site: the higher the growth rate, the sooner the saturation constraints of C sequestration will be reached.

Figure 24 shows the difference after 40 years between a scenario where land is reafforested with fast growing species to produce biomass for energy (fossil fuel substitution), and a scenario where the same land is reafforested with the main purpose of C sequestration. The colored surface (vertical axis) depicts the cumulative C benefits of the bioenergy option

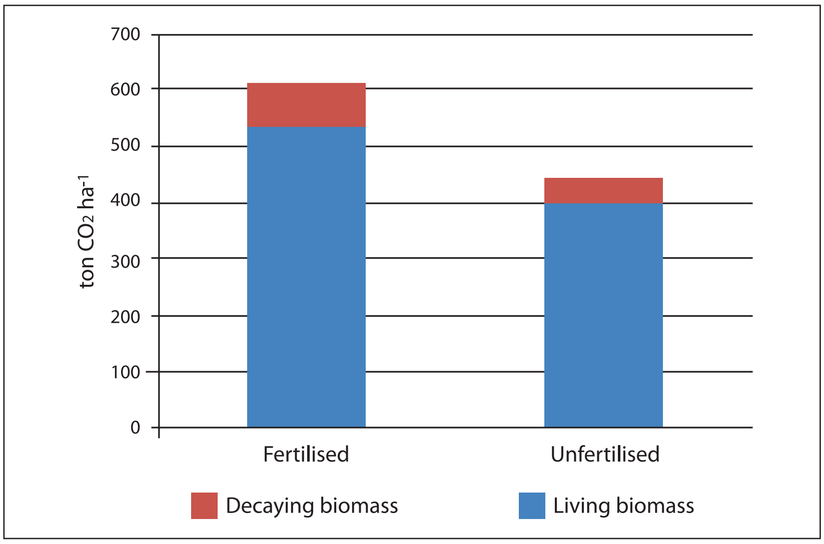


Figure 23. *Average carbon stock (ton CO_2 ha^{-1}) in living and decaying biomass in fertilised and unfertilised stands in northern Sweden, averaged over full rotation periods. The data refers to stands in northern Sweden. The difference between the fertilised and unfertilised stands would be less in central and southern Sweden*[157].

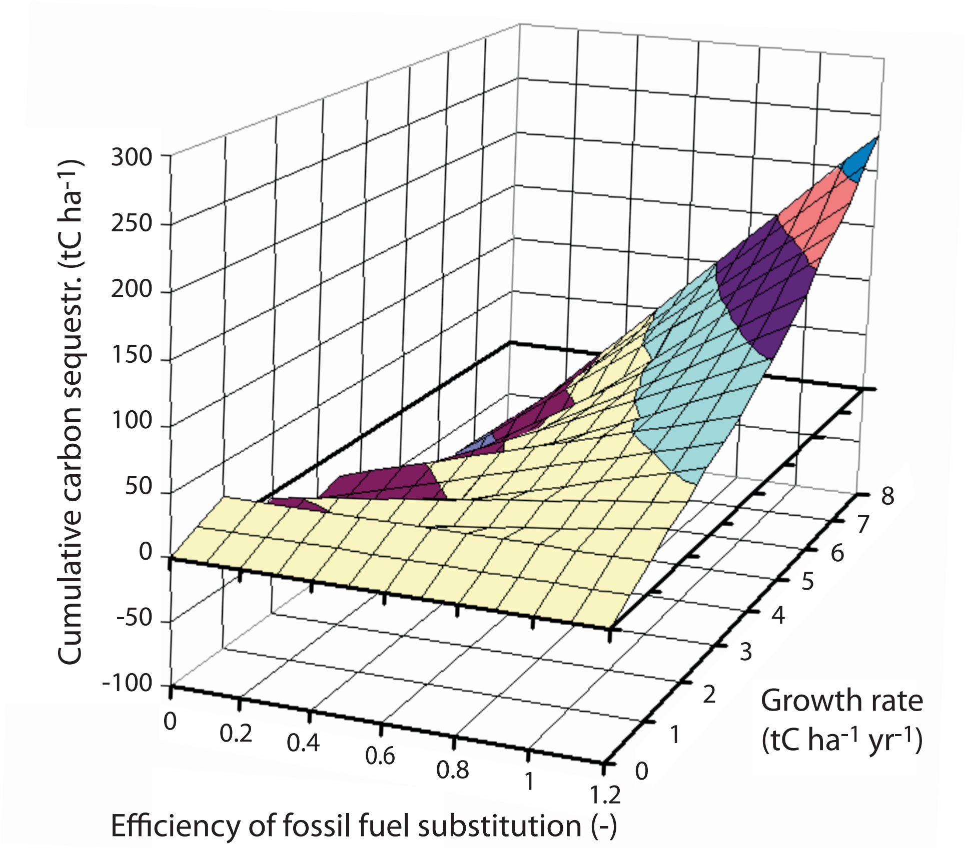


Figure 24. *An illustration of the relative attractiveness (from a GHG mitigation perspective) of afforestation for bioenergy versus for C sequestration, as a function of the efficiency of fossil fuel substitution and growth rate of the biomass plantation. The colored surface (vertical axis) depicts the cumulative carbon benefits of bioenergy over C sequestration, 40 years after the afforestation event.*

over the C sequestration option as a function of the fossil fuel displacement efficiency (a function of both the bioenergy system and the C intensity of the energy system displaced) and of the growth rate. Positive values indicate that management for bioenergy is the better choice.

As can be seen, a combination of high yielding species and efficient use of the biomass to replace fossil fuels makes bioenergy the preferable option over C sequestration. In the back right corner of the diagram the benefits of bioenergy exceed those of C sequestration by almost 250 ton of C ha^{-1} after 40 years. On the other hand, low-efficiency biomass use, independent of growth rate, means that the land is better used for C sequestration. The difference between the two options is obviously smaller when growth rates are low, meaning that the relative merits of bioenergy are limited even if the fossil C displacement efficiency is high.

As was stated in the section 'Options for Relocation of Carbon Within the Atmosphere-Bioshpere System', intentional (e.g. establishment of cropland) or unintentional (e.g. forest fire or storms) processes may lead to the C that has been sequestered in forests being emitted to the atmosphere again. Such risks present significant challenges for initiatives aiming for climate change mitigation through biospheric C sequestration. On the other hand, bioenergy systems may also function as carbon sinks or, conversely, afforestation, reforestation and revegetation can enhance C stocks in plants and soils while at the same time contributing to a future biomass resource. The inclusion of a biomass production component (for bioenergy or other uses) in projects that aim to increase forest C stocks may make these more robust in relation to various future developments.

As well as the possible variation in important factors preventing a general global ranking of forest-based options for climate change mitigation, the project level (or stand level) approach to evaluating different options in itself has limitations and needs complementary consideration on a landscape level. There is also the need to consider both a short-term and a long-term situation. As an illustration of how the design and application of C accounting systems can influence the view on forest bioenergy, consider the two cases of forest C accounting in Figure 25 shown as starting at different times but both using a 20 year time frame:

- In A, the accounting starts so as to allow consideration of the higher growth rate – and consequently higher C sequestration – achieved from fertilisation (the unfertilised forest might be used as a reference case) and the biomass extraction taking place during thinning operations is quite soon compensated for due to the rapid growth rate.
- In B, the accounting starts at the time when final harvest takes place and if a significant part of the extracted biomass

is used for bioenergy or in short-lived products, this would in most cases (depending on energy system configuration) appear as a large net C emission to the atmosphere since there is little time for forest regrowth before the accounting period ends.

As illustrated in Figure 24 the size of the net C emissions will depend on fossil C displacement efficiency and the time profile for the forest regrowth that compensates for the biomass extraction (or, in the case of forest residue extraction where the alternative (reference) situation is to leave the residues in the forest, in which case the time profile of the forest residue decay can vary considerably[158]). However, 'Project A' in Figure 25 would clearly appear to be much more favorable for the climate than 'Project B' in an evaluation that narrowly considers a distinct forest bioenergy project (either A or B) and that uses a relatively short time horizon. Yet, both 'Project A' and 'Project B' are components of the same forest management regime that have undisputable net substitution benefits (lower diagram in Figure 25).

The above example is illustrative of the limitations of narrow project-level evaluations that do not consider the broader perspective of forest management with long rotations. There is a risk that designing policies and incentives structures that use project level evaluations as a basis creates a situation where the most economic way of managing a forest is very different from how we can best shape forest management in response to future demand for bioenergy and other forest products while also considering longer-term political climate targets such as the 2°C target in the Copenhagen Accord, which ultimately require far reaching energy system transformation.

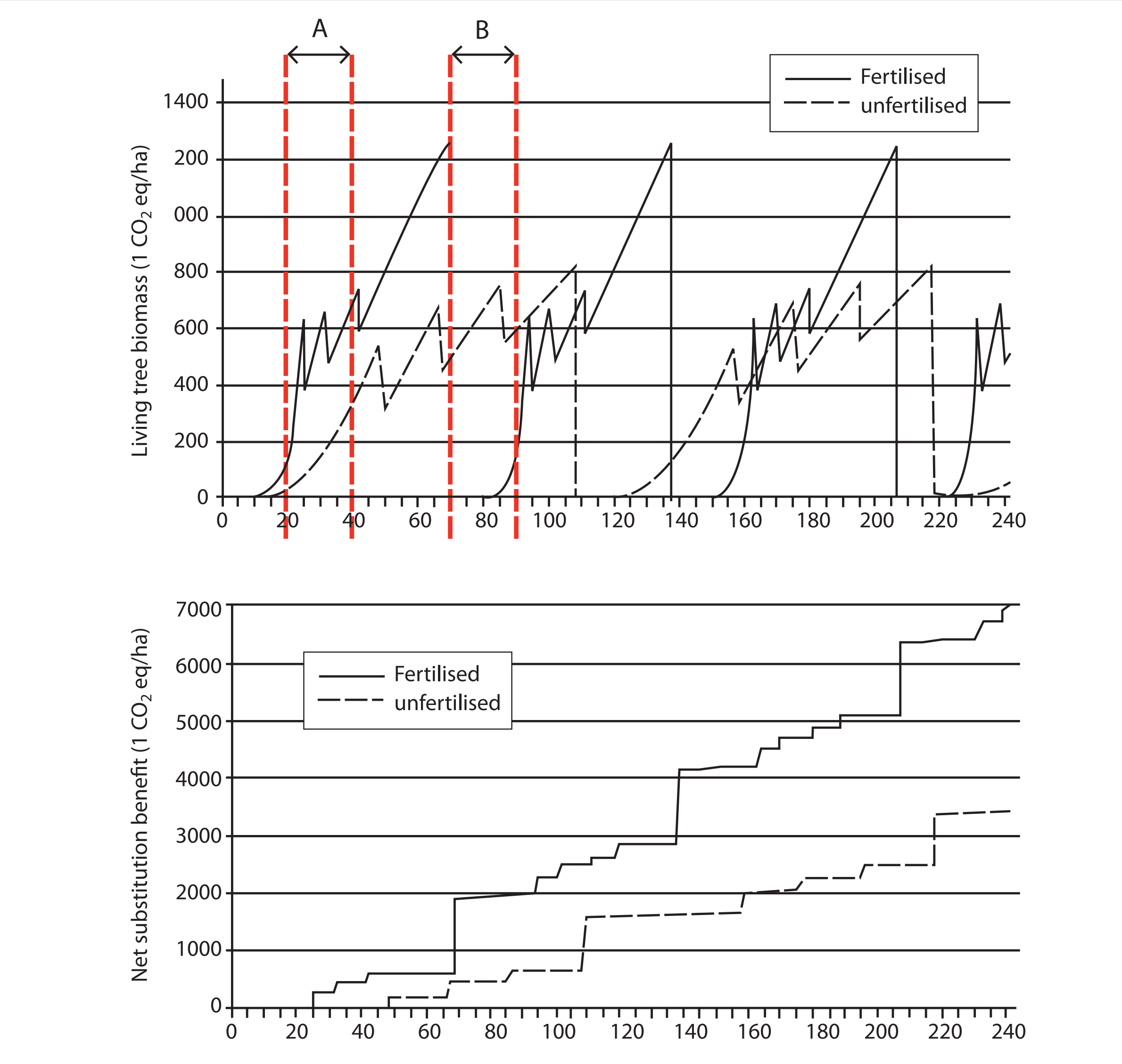


Figure 25. *Development of carbon stocks and GHG flows over a 240-year period for typical fertilised and unfertilised stands in northern Sweden. The top diagram shows living tree biomass and the bottom diagram shows net substitution benefits of wood product use assuming coal reference fuel, with deductions made for N_2O, CH_4 and fossil CO_2 emissions[157]. The dynamics of C in soils and dead biomass (not shown) is highly influenced by the forest management but occurs at a smaller scale (fluctuations are within 250 ton CO_2 ha^{-1}). A and B denotes two possible cases of forest bioenergy accounting (see text).*

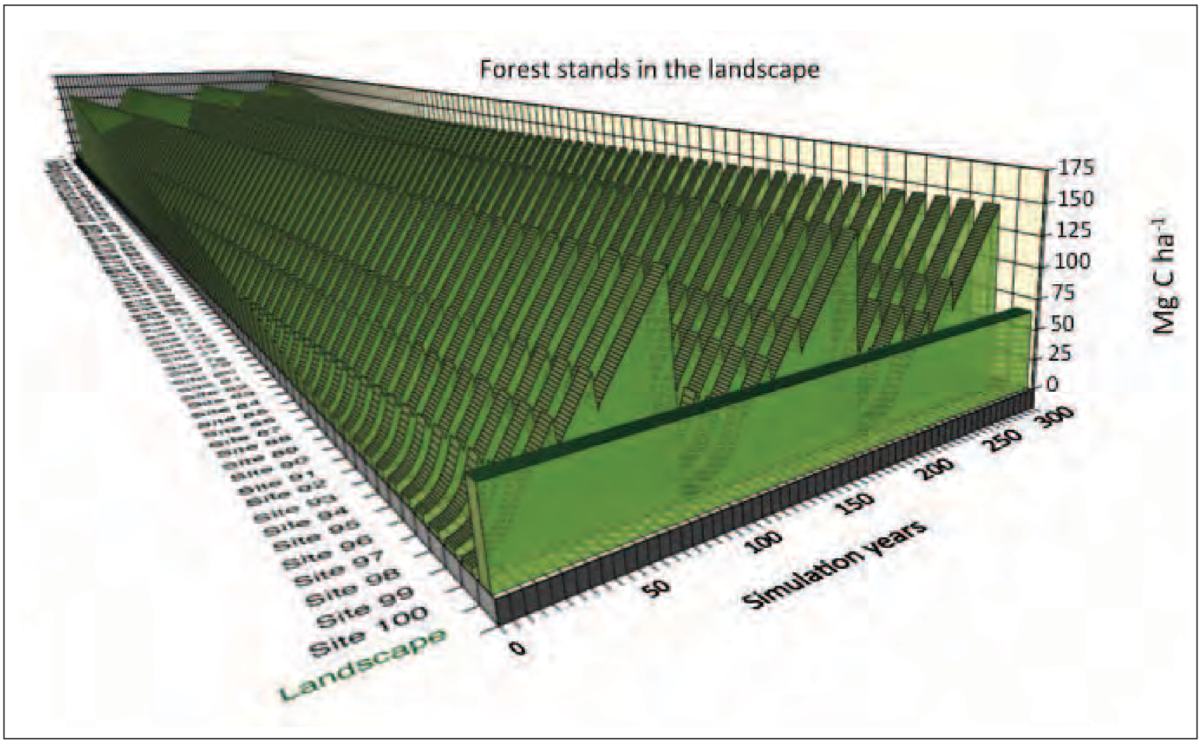


Figure 26. *Tree biomass in a chronosequence of 100 identical simulations of Norway spruce stands in southern Sweden as shown in Figure 22. Each stand is planted one year after the other starting from year 0. The average C content of the trees included each year is shown in the front most bar representing the landscape level.*

Illustrating the difference between stand level and landscape level, Figure 26 again shows the case of the Norway Spruce forest in southern Sweden (shown on a stand level in Figure 22), but this time at landscape level. The mosaic of forest stands at different age classes that characterises long-rotation forestry is represented here by 100 stands where each individual stand is of a different age. The losses and gains of C from individual forest stands in the landscape counterbalance. The C balance per hectare from each stand at any given year contributes with 1/100th of the aggregate balance at any year.

Figure 26 also gives an indication to how the forest C stock at the landscape level may be influenced by changes in the conditions for forest management (policy, regulation, etc.). If, for instance, a new policy is implemented in a given year – and this policy changes practices for forest planting, thinning and final felling – then one stand is planted, one is harvested and three stands are thinned according to the new policy this specific year. Thus, not all stands are immediately influenced by a new policy; a given stand remains under the 'old' management regime until the next thinning, or until final felling when planting occurs.

For the purpose of illustrating how the C dynamics differ at the stand and the landscape level, Figure 27 shows how forest C stocks vary for three forest management and harvesting scenarios at both levels. The 'Stems Only' scenario is the same as shown in Figure 22 and Figure 26, i.e. harvest residues are left on the ground both after thinning and final felling. The 'Stems & GROT' scenario involves extraction of 80% of the logging residue after thinning and final felling (GROT is the Swedish acronym for branches and tops – GRenar Och Toppar in Swedish), and the 'Stems, GROT & Stumps' scenario includes in addition the removal of 50% of stumps-coarse root systems at final felling.

The modelled changes over time of C stocks in soil, trees, and ecosystem (trees + soil) are shown together with the C in the cumulative biomass harvest. As can be seen there are no major changes in soil C stocks in the simulations. The 'Stems Only' case leads to a small increase while increased harvest intensities slightly decrease the soil C. If the intensification of harvest were to be implemented together with productivity-enhancing measures, soil C stocks would likely instead have increased (Figure 25).

The differences of accumulated harvested biomass and losses in soil C between the 'Stems Only' scenario and the intensified harvest scenarios can be seen in Figure 28. In other words, Figure 28 shows the net C effect of changing the forest biomass extraction to also include felling residues that can be used for energy. The benefit of increased harvest occurs immediately, growing linearly over time whereas the associated loss of soil carbon has a delayed and declining response. Thus, losses of soil C are, compared to accumulated harvested biomass C, greatest in the beginning of the period following the change in forest management. The landscape soil C stocks initially declines in response to intensified harvests and stabilise over time.

Mean annual increment and thus the rate of accumulation of soil C in an established plantation is expected to eventually

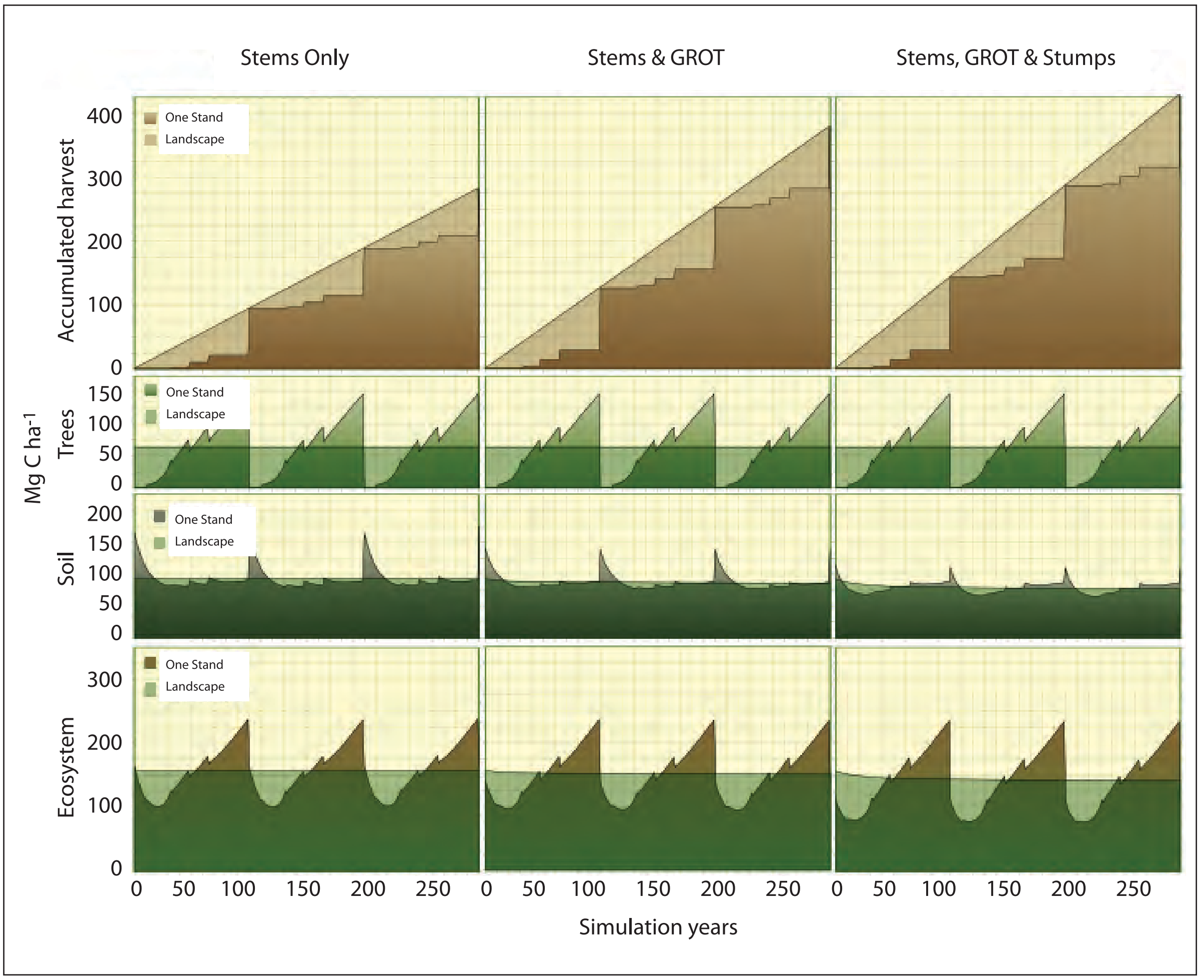


Figure 27. *Development of C stocks Norway spruce forest in south Sweden subject to three different management practices (described in the main text)[151]. The single stands are plotted behind the landscape averages in the foreground.*

decline if no future harvesting occurs (the option of reverting a managed and harvested forest to a primeval condition was modelled but this case is not shown in Figure 27). However, as noted earlier in this report, observations indicate that old forests, which commonly have been presumed to be neutral in their C exchange with the atmosphere, can also be net carbon sinks and that the fertilisation effect of increasing atmospheric CO_2 may be one explanation to this.

The total C balance, where the accumulated harvests are also included, is considerably increased in the harvested systems. The losses in ecosystem C are considerably less than the corresponding withdrawals. From the perspective of climate change mitigation – besides the selected time scale in evaluations – the relative attractiveness of primeval versus harvested forests depends on the net GHG savings associated with the use of the harvested biomass, as illustrated in Figure 24.

As for agriculture-based bioenergy discussed earlier in this report, the contribution of forest bioenergy to climate change mitigation needs to be evaluated from several points of view, reflecting a balance between near-term targets and the long-term objective to hold the increase in global temperature below 2°C (Copenhagen Accord). Adding landscape perspective considerations to complement project level indicators and metrics is one important step, but additional perspectives are also needed. This is further discussed in the section 'Bioenergy and LUC in the Context of Global Climate Targets'.

Climatic Consequences of Other Changes Associated with LUC

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

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

The albedo of a surface is the extent to which it reflects light from the sun. Depending on its colour and brightness, a change in land surface cover can have a positive (cooling) or negative (warming) effect on climate change. A darkening of the land surface causes warming since more of the solar radiation is absorbed. A lightening of the land surface has the opposite effect, ie, cooling.

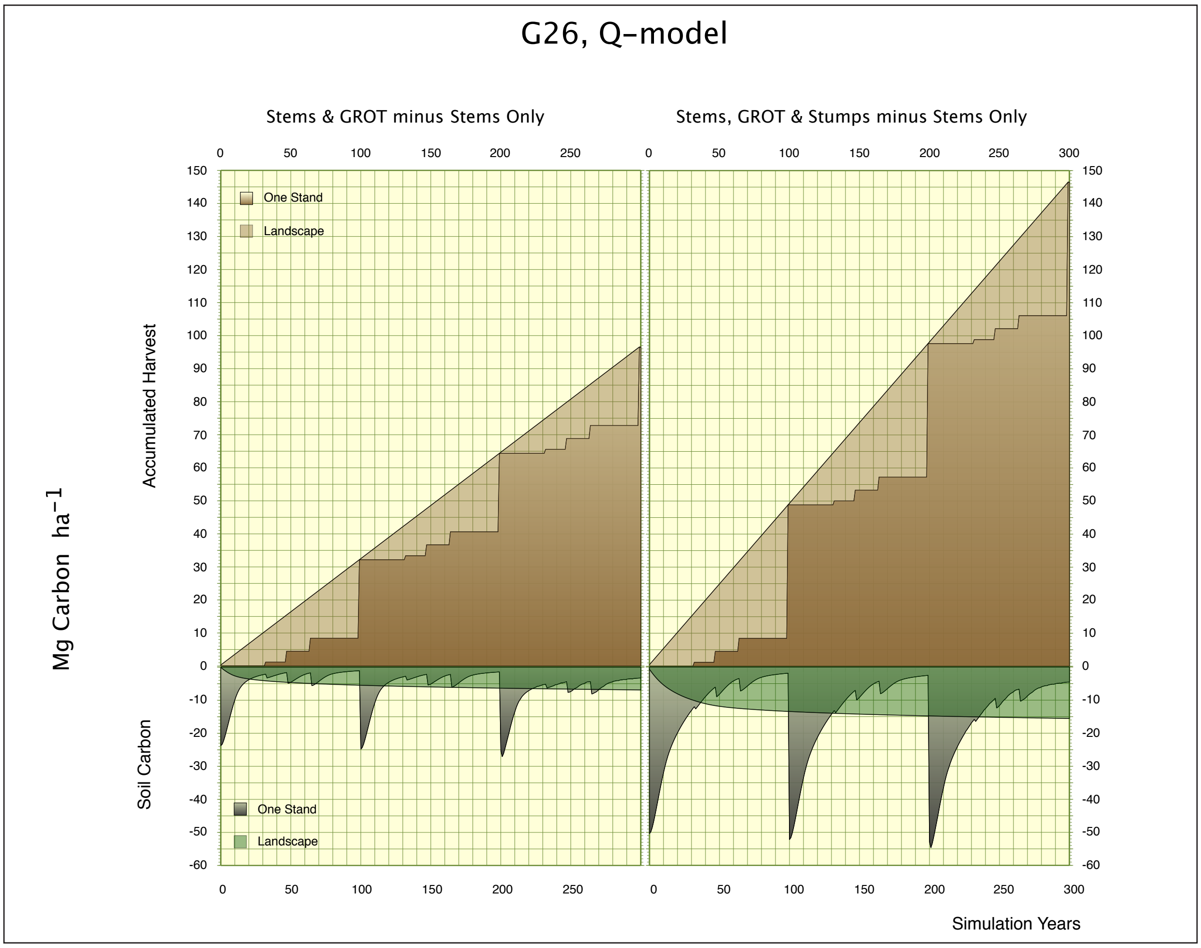


Figure 28. *Effects on the C balance of increased removal of felling residues. The increased residue removal starts year 0 and continues over the whole 300-year period. Upper panes show the amount of removal in comparison to the Stems Only scenario and lower panes the corresponding loss of soil C. Single stands are plotted behind the landscape averages in the foreground.*

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 a 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. It has also long been questioned whether planting coniferous trees in areas with snow is an effective climate mitigation measure since the darkening of the surface (decrease in albedo) may contribute to warming[159]. For example, it has been reported that (i) the change in surface albedo due to planting coniferous forests in areas with snow cover can contribute significantly to radiative forcing[160]; (ii) cooling due to albedo change from deforestation was of the same order of magnitude as increased radiative forcing from CO_2 and solar irradiation[161]; and (iii) a global-scale deforestation event could have a net cooling influence on the Earth's climate[162].

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. savannahs) 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. For example, it has been reported that in Brazil, changing the land surface from Cerrado vegetation to pasture or sugarcane increases the warming due to a darkening of the land surface, while changing from pasture to sugarcane causes cooling due to an increase in albedo (lightening)[163]. A study that modelled a hypothetical conversion of cropland to perennial bioenergy crops in the central USA found that the benefit from albedo-derived climate cooling was six times larger than the climate benefit caused by offsetting fossil fuels[164]. Thus, the albedo change that may be associated with bioenergy can be highly influential on the net climate outcome and therefore important to consider.

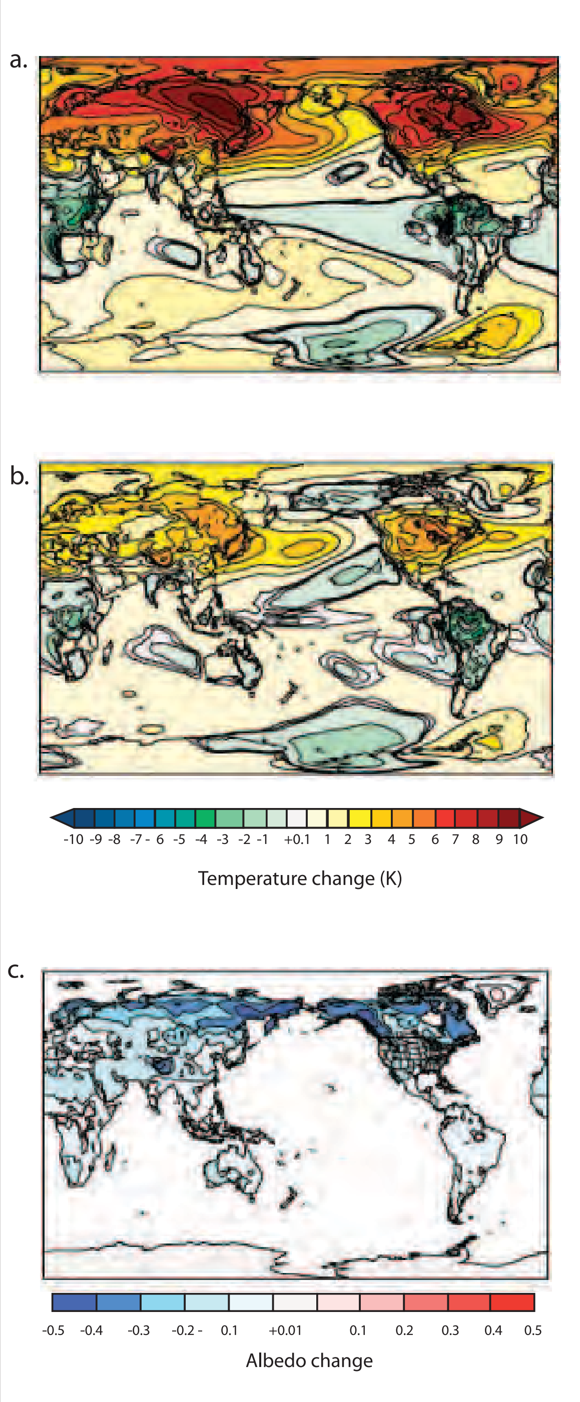


Figure 29. *Albedo and direct warming consequences of forests. Panel a: Direct warming associated with global forest cover. (These are results from a forest-covered world minus the results for bare ground). Forests produce over 10°C of warming in parts of the northern hemisphere due primarily to increased absorption of solar radiation. Forests produce several degrees of cooling in tropical areas, primarily due to increased evapotranspiration. Panel b: Direct warming associated with forest cover between between 20°N and 50°N. (These are results from actual vegetation with added forests in the mid-latitudes minus the results for bare ground.) Mid-latitude forests can produce warming locally of up to 6°C (10°F). Panel c: Increase in fractional absorption of solar radiation at the ground for forests relative to bare ground. Source: Lawrence Livermore National Laboratory (www.llnl.gov/news/newsreleases/2005/NR-05-12-04.html, retrieved April 4 2011).*

Figure 30 shows the albedo of various land covers. Forests and wet soils have very low albedo (dark). Savannah, deserts and dry soils are lighter (higher albedo). Snow can have very high albedos, but there is a variation depending on the age of the snow cover. Meadows and crops have a fairly wide range of albedo depending on the time of year and drought situations. Typical land cover changes associated with bioenergy include:

- Short-rotation forestry on meadows, cropland or degraded land. This would cause a decrease in albedo (hence warming).
- Short-rotation forestry on meadows or cropland that have snow in winter. This has a particularly pronounced albedo change.
- Conversion of savannah to meadows (for biogas for example). This darkens the surface and causes albedo-induced warming[163].
- Conversion of meadows to cropland (for example, sugarcane, corn or rape seed). This may decrease the albedo, but it depends on the fraction of the year that bare soil is exposed[165].

A methodology has been developed for combining albedo and C stock changes into either radiative forcing or CO_2 equivalence[166]. Analyses using the methodology show that afforestation of savannah or meadow with snow in winter causes increase in carbon stocks (i.e. emission reduction) that is nearly the same as the counteracting albedo change. In other words, the net change in global warming is small. The reason that the afforestation of savannah results in a similar net change in global warming as afforestation of meadows with snow in winter is that the warming is a combination of albedo change and incident solar radiation. The incident solar radiation is higher in the savannah case than for meadows with snow in the winter. However, based on the present state of science it is tentatively concluded that the albedo-induced climate effect is in general opposite to the climate effect caused by a change in C stocks. Coming back to the above examples of typical land cover changes due to bioenergy mentioned above:

- Conversion of cropland or grassland to forest causes an increase in C stocks (cooling) but a darkening of the surface (warming).
- Conversion of savannah to irrigated meadow causes a darkening of the surface (warming) and increased C stocks (cooling).
- Conversion of grassland or meadow to cropland causes a decrease in C stocks particularly in soils (warming) and a varied change in albedo depending on the fraction of the year that bare soil is exposed.

The integration of climate change effects associated with albedo change and a C stock change is still in its infancy and several challenges remain. The combined effects are particularly sensitive to the true albedo change – including atmospheric effects and clouds – and this is often not measured[167]. Models can be used to estimate the true albedo[168] but there is a need for true satellite-based measurements. For forests, this includes measuring the combined effects of the amount and timing of canopy closure and its relationship to yield. Furthermore, as mentioned

LUC can also lead to changes in evapotranspiration and, besides the cooling effect of evapotranspiration itself, this can influence the cloud cover which in turn influences the true albedo. It needs to be noted that the pattern of warming from a CO_2 change and albedo change differ from each other and results from simulations to study the influence of irrigation on climate gives reason for questioning the applicability of the radiative forcing concept for such a climatic perturbation[22].

Areas little researched so far include the effects of negative feedbacks and albedo changes due to a change in aerosols. Combustion of bioenergy causes different aerosol emissions than combustion of fossil fuels and this may cause a change in albedo when bioenergy displaces fossil fuel combustion.

To conclude, the integration of albedo and C stock changes is an important aspect to consider when estimating the climate change impacts of bioenergy, but more research is needed before firm conclusions can be made. The limited papers that have been published support the tentative conclusion that, in general, the change in surface albedo counteracts the climate change impacts from losses or gains in C stocks. It can also be concluded that the influence of albedo changes on the climate change benefits of bioenergy can be large.

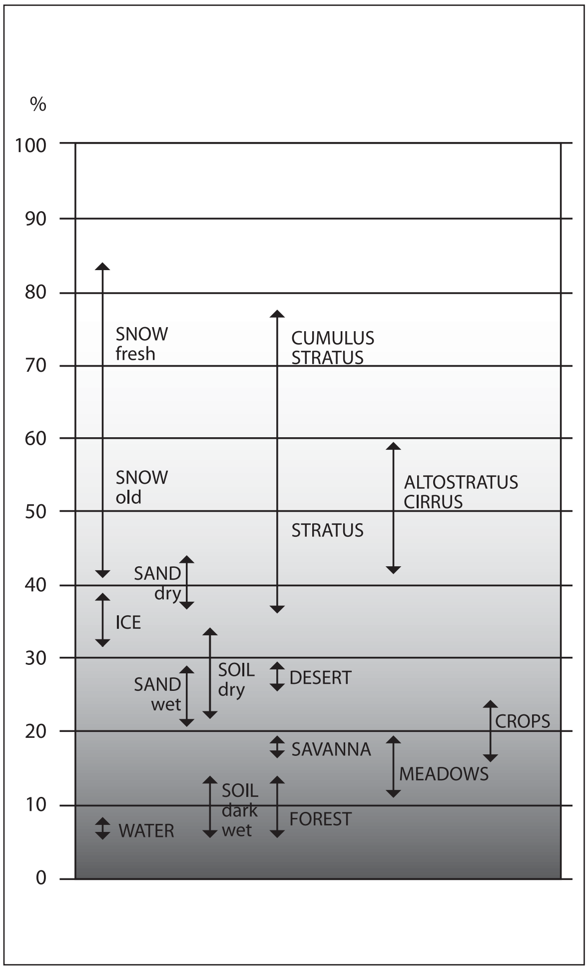


Figure 30. *Albedo of various land cover types.*

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[169]. There is also scope for sizeable improvements in land use efficiency for livestock production and dietary changes towards less land-demanding food[170]. For example, shifts from ruminant meat to pig and poultry consumption and increased vegetable consumption can reduce land requirements for food production substantially[171].

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[172]. This would further reduce the LUC pressure associated with food and bioenergy development.

However, 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 – including emission of the greenhouse gas N_2O – reducing the climate benefits of strategies that aim at reducing LUC emissions through land use intensification[173]. As noted above, climate change will affect conditions for food, fibre, as well as bioenergy feedstock production and water scarcity can limit both possible intensification and the prospects for expansion in some locations, although this can be partially alleviated through on-site water management[174]. Negative trade-offs might to some extent 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.

Agricultural productivity can be increased in many regions and systems with conventional or organic farming methods, avoiding some of the drawbacks of intensification[175]. Significant potential to improve 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[176]. Conservation agriculture and mixed production systems (double-cropping, crop with livestock, and/or crop with forestry) have the potential to improve land use efficiency[177]. Available best practices are not at present applied in many world regions due to a lack of information dissemination, capacity building, and access to capital and markets[178]. 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 outlined in the section 'Bioenergy and Land Use Change', bioenergy feedstocks may be one output from integrated biomass production systems. Examples of such systems include various multifunctional biomass production systems that have been proposed for the provision of extra environmental services (in addition to the biomass output). Some are developed to provide *direct* environmental services, while others provide environmental services of a more general nature. The underlying idea – that certain plants can be cultivated in certain ways to provide various benefits in addition to the harvest – has probably always influenced land use strategies. Specifically for bioenergy, integration of different perennial grasses and short-rotation woody crops has been suggested as a way of remediating many environmental problems, including biodiversity loss[179].

Many of these systems also contribute to reducing land demand for food. In an example already mentioned, soil C accumulation leads to improved soil fertility and enhanced climate benefit. Agroforestry systems are well-known examples that can increase productivity in rain-fed agriculture by capturing a larger proportion of the annual rainfall in areas where much of the rainfall occurs outside the normal growing season (see the example where *Eucalyptus* spp. is integrated with cattle production in Figure 12). Specific cases of agroforestry systems include trees that are planted as windbreaks reducing wind erosion, or integrated into the landscape to mitigate floods and reduce water erosion, in both cases reducing soil productivity losses and thereby cropland demand. Besides the on site benefits of reduced soil losses, there are also off site benefits, such as reduced sediment load in reservoirs and irrigation channels, as well as reduced deterioration in the quality of river water due to the suspended load that accompanies flood waters formed mostly by runoff.

Specific biomass plantations can reduce other types of soil degradation, such as when willow cultivation reduces the cadmium content in topsoil, making it possible to continue cultivating crops for human consumption[180]. Large-scale plantings of trees are used for salinity management on land subject to productivity losses due to soil salinity induced by rising water tables (typically due to replacement of forests with pastures or other vegetation types having lower evapotranspiration rates than the original forests). Biomass plantations with high water usage that are planted to intercept water moving through the soil reduce ground-water recharge, and if planted up-slope of salt-prone areas instead, they can contribute to preventing salinity by reducing the amount of water reaching the recharge zones. When planted within salt-prone areas, plantations can lower the water table and also reduce evaporation losses by providing ground cover[181].

Figure 31 shows one example of a vegetation filter plantation that is used for the treatment of pre-treated municipal wastewater. Phosphorous and nitrogen in the water are captured in the plantation which prevents eutrophication in nearby lakes and streams. In addition, the plantation yield is significantly higher than in conventional plantations due to the irrigation. Plantations can be used as vegetation filters in many ways; such as for the treatment (via irrigation) of nutrient-bearing water such as wastewater from households, to collect run-off water from farmlands and leachate from landfills. Plantations can also be located in the landscape and managed as buffer strips for capturing the nutrients in passing run-off water. Furthermore, sewage sludge from treatment plants can also be used as fertiliser in vegetation filters[182].

The integration of bioenergy and food production can also take place at the feedstock conversion level. Existing examples of such integrated production include cereal ethanol production and oil seed biodiesel production, which generate animal feed as a co-product displacing cultivated animal feed such as soy and corn and also reduce grazing requirements (with LUC consequences as illustrated in Figure 18). Studies point to promising opportunities for reducing land requirement by implementing land efficient systems to provide biomass for both the food and biofuel sector. Among examples, Dale *et al.* (2010)[183] show how combined production of animal feed and biofuel feedstock on 30% of total USA cropland, pasture, and range, allow the production of 400 billion litres of ethanol per year without decreasing domestic food production or agricultural exports. Integrated production can also provide additional benefits by increasing soil fertility and promoting biodiversity.

Integrated production of sugarcane ethanol and meat/dairy production in Brazil is another example[184]. In this case, farmers allocate part of their land to sugarcane production and receive in return an income flow that they can invest in higher productivity cattle and improved pastures. They also receive a protein rich feed from the ethanol factory, which serves as a valuable feed complement during the winter season when the pastures are not grazed. The net outcome is that the dairy/meat output increases substantially while ethanol is also produced. Analyses also indicate that the farmers' economic

Figure 31. *View of municipal wastewater plant, with water storage ponds and (behind the ponds) willow fields that are used as vegetation filters for the treatment of pre-treated municipal wastewater. The photo is taken from the roof of the heat and power plant that uses the locally produced biomass. Courtesy: Pär Aronsson, Swedish Agriculture University.*

situation will improve very significantly if they shift to this integrated ethanol/dairy production[185]. Besides representing an option for improving land use efficiency, integrated ethanol/dairy system may reduce the iLUC risk, since farmers invest in their existing land use instead of using the income they get from selling/renting out land to the sugarcane industry to make new land investments elsewhere.

Thus, the system may be one example of a LUC-minimising expansion strategy when pasture areas are targeted for sugarcane expansion. Productivity increases in meat and dairy production can also be achieved based on other means. This represents a substantial opportunity to free land for producing bioenergy feedstock, since land use efficiency is presently very low in many parts of the world[186]. In the case of sugarcane production, shifting from manual harvest with field burning to mechanical harvest can also mitigate LUC emissions. This reduces soil C emissions from converting pastures with high C content into sugarcane plantations since the carbon input via residues balances the loss of soil carbon from tillage. In some instances, sugarcane cultivation employing mechanical harvest may lead to soil C increase[187].

It is important to note that biospheric C losses to the atmosphere, causing LUC emissions, can be reversible. In fact, one major reason that promising opportunities exist for biospheric C sequestration is that human activities have earlier caused biospheric C losses from the same locations. Soils have historically lost some 40–90 Pg C globally through cultivation and disturbance, and cultivated soils can contain less than half of the original SOC. Much of this lost C can be returned through LUC and changed land management practices. Figure 32 presents one illustrative case showing how the affected C pools can change over time. The diagrams show the accumulated C benefit of reforesting sparsely vegetated land with relatively low soil C levels, which for instance could be the result of earlier cultivation of conventional annual food crops. 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 refers to a case where soil C is low. If instead pastures containing large soil C stocks were converted to plantations, there might be up-front soil C emissions as a result of establishment operations. Finally, once again, the net C effect of the conversion would depend on the incidence and extent of iLUC associated with the reforestation initiative.

Achieving the desired changes in land management around the world, to increase C in soils and above ground vegetation, is not an easy task. Some processes causing biospheric C losses can lead to ecosystem states that can be difficult to change back to the earlier states: unsustainable land use practices can for instance degrade soils to a condition where the original vegetation and productivity cannot be sustained. In some situations economic rather than biophysical barriers prevent the recapturing of lost biospheric C. For example, croplands established on former forestland are as a rule not re-forested again as long as they provide positive revenues from the cultivation.

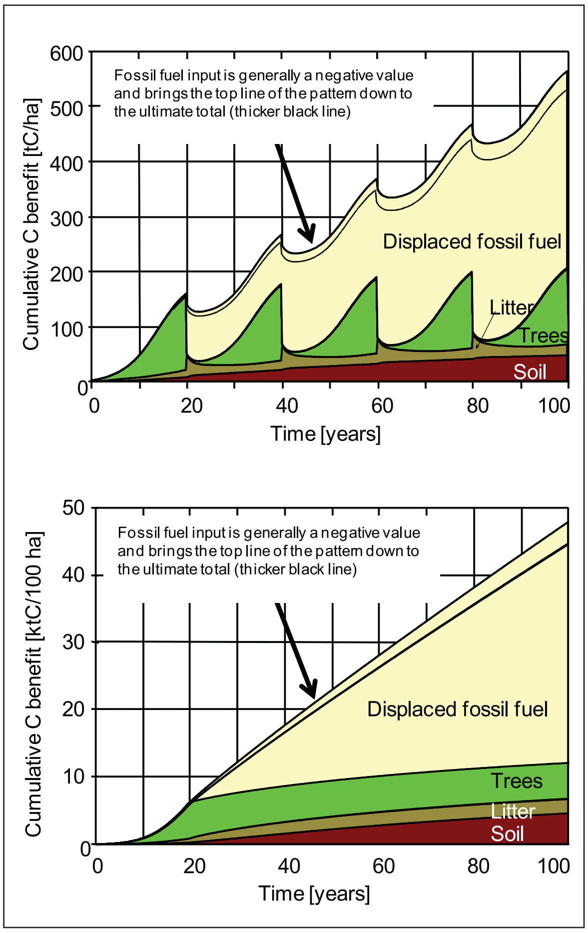


Figure 32. *Reforestation (year one) of sparsely vegetated land having relatively low soil C level, with subsequent use of the harvested biomass for energy. The cumulative climate benefit is shown on the 1-hectare stand level (top) and on the 100-hectare landscape level – i.e. a plantation system producing 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).*

While broad-scale reforestation is not likely to be a viable strategy for increasing soil C on cropland, shifts to new cropland management systems and/or new types of crops may be encouraged by economic incentives connected to prospective C markets. The development of bioenergy markets can also become an important driver in this regard. The option to produce new types of crops such as perennial grasses and short-rotation woody plants for energy markets gives farmers new opportunities in their land use. As described above, the establishment of such plants can, through well-chosen location, design, management and system integration, help the reclamation of degraded lands and also offer other socio-economic and environmental services that, in turn, create added value for the systems. Extensive information can be found in the growing number of publications describing the environmental effects of implementing lignocellulosic feedstock cultivation[188]. The targeting of degraded/marginal land is further discussed in the next section.

Figure 33. *Agricultural landscape in Sweden. Conversion of forests and other natural ecosystems to agriculture land has resulted in substantial biospheric C losses. Some of the lost C can be sequestered again through changed land management practices and by cultivating new types of plants including trees. The willow plantation in the background of the photo is one example of a plantation system that can induce soil C sequestration when established on lands that have long been cultivated with annual crops. Photo courtesy of Pär Aronsson, Swedish Agriculture University.*

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 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 would otherwise be 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.

However, exploitation of harvest residues is one important cause of soil degradation in many parts of the world[189]. Fertiliser inputs can compensate for nutrient removals connected to harvest and residue removal from the fields, but maintenance or improvement of soil fertility, structural stability and water holding capacity requires recirculation of organic matter to the soil[190]. To the extent that residue extraction prevents nutrient replenishment and causes soil degradation leading to soil productivity losses over time, more cropland will be needed to meet the required level of future food/fibre/bioenergy demand. There is a risk of this causing iLUC emissions since the cropland expansion may cause vegetation removal and ploughing of soils, leading to substantial C losses to the atmosphere. Thus, the use of residues as bioenergy feedstock needs to carefully consider site-specific constraints on extraction rates. Otherwise, more rather than less land may be required in the longer-term, as cultivation needs to expand to compensate for soil productivity losses.

The production of bioenergy feedstocks on marginal/degraded lands, where productive capacity has declined temporarily or permanently, represents an option for reducing LUC effects and potentially obtaining additional benefits such as C sequestration in soils and above ground biomass and improved soil quality over time. The conversion of extensively used pastures to biofuel plantations has been proposed as one option for expanding biofuel production in Brazil that has a lower risk for causing undesirable iLUC. In another example, targeting degraded lands for oil palm expansion may reduce the pressure on the remaining forests and avoid substantial LUC emissions[191]. A third example, afforestation and *Jatropha* planting, is considered an option for making productive use of so-called wastelands in India, which cover about 50 Mha or 16% of the Indian land area[192].

Advances in plant breeding and genetic modification of plants not only raise the genetic yield potential but may also be used to adapt plants to more challenging environmental conditions[193]. Improved drought tolerance can improve average yields in drier areas and in rain-fed systems in general by reducing the effects of sporadic drought, and can also reduce water requirements in irrigated systems[194]. Thus, besides reducing land requirements for meeting food and materials demand by increasing yields, plant breeding and genetic modification could make lands earlier considered as unsuitable, available for rain-fed or irrigated production.

In addition to the low productivity of degraded/marginal land in itself presenting a significant barrier, the large effort and long time period required for the reclamation and maintenance of degraded lands can be a challenge. Land reclamation projects also need to ensure that the needs of local populations that use degraded lands for their subsistence are carefully addressed. In addition, possible water consequences need to be considered[195]. The use of degraded/marginal areas with sparse vegetation for establishing high-yielding bioenergy plantations can lead to increased evapotranspiration of groundwater and surface water, which may lead to substantial reductions in downstream water availability. This may become an unwelcome effect requiring the management of a trade-off between upstream benefits and downstream costs. Rain-fed feedstock production does not require water extraction from water bodies, but it can still reduce downstream water availability by redirecting precipitation from runoff and groundwater recharge to crop evapotranspiration[196]. Catchment level planning and careful design and management of plantations based on consideration of the specific hydrological conditions can however avoid or at least mitigate water-related impacts.

Local stakeholder participation in appraising and selecting appropriate measures can be a way to integrate the local context in land use planning, and land degradation control could also benefit from addressing aspects of biodiversity and climate change[197]. This might also pave the way for funding via international financing mechanisms and major donors[198]. In this context, the production of properly selected plant species for bioenergy can be an opportunity, where additional benefits involve C sequestration in soils and above ground biomass, and improved soil quality over time. Again, the integration of biofuel production with cattle rearing on pastures is a prime example.

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. In one example of such an approach, the EC Renewable Energy Directive includes sustainability criteria (Article 17) requiring that 'biofuel and bioliquids… shall not be made from raw material obtained from land with high carbon stock, namely [further specified in the Directive]'.

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, as discussed above, 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 suitable areas for sugarcane and oil palm expansion. The Brazilian sugarcane agro-ecological zoning intended to guide the sugarcane expansion includes several components:

- the identification of areas without any environmental constraints that are already degraded or under human use that have potential for sugarcane cultivation;
- the exclusion of the biomes of Amazon, Pantanal and Upper Paraguay River Basin for sugarcane expansion; and
- the indication of degraded land or pasture areas as preferable areas for sugarcane expansion, minimising any competition with food production.

Specific areas were also excluded from the agro-ecological zoning for sugarcane: protected areas, indigenous reserves and areas with high conservation value for biodiversity.

To summarise, there are many options for avoiding or mitigating LUC emissions from bioenergy expansion, but there are also several shortcomings and challenges to address:

- Although land use restrictions applied only for biofuels feedstock cultivation could decrease indirect impacts on LUC, land use restrictions are more effective to avoid the indirect effects of bioenergy expansion if they become internationally recognised and are 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, while many highly productive lands have low natural biodiversity, the opposite is true for some marginal lands and, consequently, the largest impacts on biodiversity could occur with widespread use of marginal lands.
- 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 the LUC emissions and the GHG savings achieved from the fossil fuel substitution. A total exclusion implies that only a short-term perspective is used to guide the strategic planning for bioenergy.

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 34 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.

The two lower trend lines in Figure 34 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 GHGs other than CO_2. In the CO_2-Stab 1 scenario deforestation is reduced as in the BAU

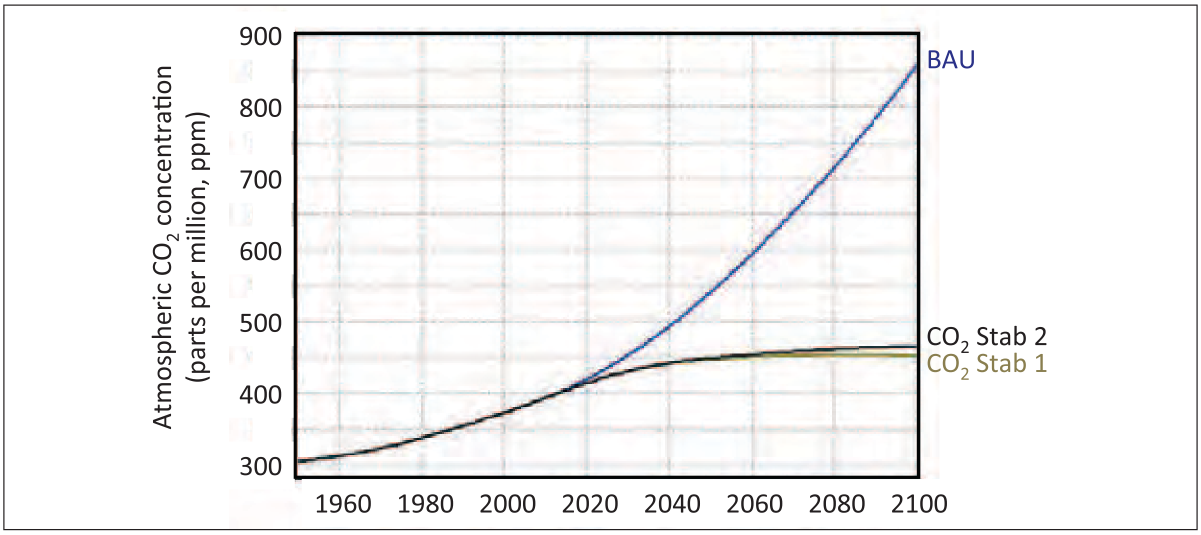


Figure 34. *Changes in atmospheric CO_2 concentration associated with three different GHG emission pathways, as described in the text. The diagram is produced using the Chalmers Climate Calculator, available at www.chalmers.se/ee/ccc.*

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 strictly due to the differences in fossil fuel emissions. Meanwhile, the large differences in deforestation rates and associated LUC emissions result in a 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 34, 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 34 that are valid for the full range of such studies:

- Stabilisation of atmospheric CO2 concentrations at levels proposed in relation to the 2°C 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. Global cumulative C emissions up to 2050 and emission levels in 2050 are robust indicators of the probability that the increase in global temperature stays below 2ºC relative to pre-industrial temperatures. Peak warming appears to be insensitive to the emission pathway, i.e. the timing of emissions or the peak emission rate[199]. Depending on the atmospheric lifetime of specific GHGs the trade off between emitting more now and less in the future is, in general, not one to one. However, the relationship for CO_2 is practically one to one, so that one additional ton of CO_2 emitted today requires the reduction of future CO_2 emissions by one ton. The reason for this is the close to irreversible climate effect of CO_2 emissions[200]. Nevertheless, mitigation efforts over the next two to three decades will have a large impact on opportunities to achieve lower stabilisation levels, not the least because of the long lifetime of energy infrastructure, so that present day investments in energy systems have implications for GHG emissions several decades into the future[201].

Thus, many different emission trajectories are compatible with a given target. The ceiling on GHGs 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 35, 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. As said above, 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.

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. One example already mentioned, 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

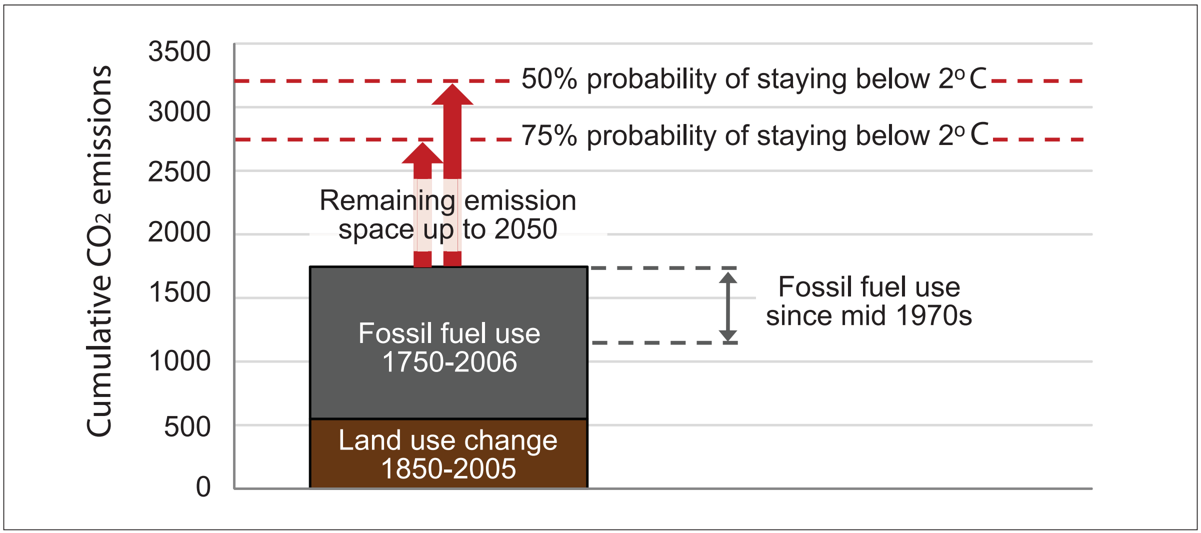


Figure 35. *Cumulative CO_2 emissions and indicative remaining emission space in relation to a two degree target.*

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, possible LUC emissions associated with bioenergy expansion will decrease over time as above ground biomass and soil C stabilise at new equilibrium levels, and other GHG emissions decrease as 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, unfavorable near-term GHG balance due to LUC emissions does not disqualify bioenergy from being part of a long-term solution to the climate problem.

From the perspective of temperature targets and emission space, the exact shape of forest C fluctuations (such as those shown for the selected forest bioenergy cases above) is not relevant. It does not matter whether C in forest residues is emitted to the atmosphere early after the forestry operations take place (such as when used for energy) or is emitted during a longer time period (such as when the residues are left in the forest to decay). What matters is whether forest bioenergy systems are part of a changed forest management paradigm that results in systematic decreases or increases in the forest C stocks. If increased production and use of forest bioenergy results in a systematic decrease of forest C stocks, this needs to be evaluated while considering the effects of forest bioenergy use on GHG emissions from the total energy system. However, the need to manage other impacts, such as on biodiversity, water and soil conservation, should not be forgotten.

Bioenergy and land use under a LUC carbon pricing regime: As noted above, the thesis that the pricing of C from LUC emissions is sufficient to protect forests is both supported[202] and challenged[143]. While there is agreement that pricing LUC carbon emissions could potentially make many of the current proximate causes of deforestation unprofitable, the question whether it will always suffice to make forest conversion to bioenergy plantations unprofitable is debated.

While there is no consensus among researchers, it may be tentatively concluded that forest conversion to highly productive bioenergy plantations may in some places represent a cost-effective strategy for climate change mitigation, i.e. from a strict climate and cost efficiency perspective some level of upfront LUC emissions may be acceptable noting the climate benefits of subsequent continued biofuel production and fossil fuel displacement. Clearly, the balance between bioenergy expansion benefits and LUC impacts on biodiversity, water and soil conservation is delicate and the development of bioenergy and other land-based strategies to address climate change needs to consider that climate change mitigation is just one of many rationales for ecosystem protection.

An additional conclusion is that stronger protection measures than C pricing may be needed to meet the objective of tropical forest preservation. It should be noted that strict focus on the climate benefits of ecosystem preservation may put undue pressure on valuable ecosystems that have a relatively low C density. While this may have a small impact in terms of climate change mitigation, it may impact negatively on, for example, biodiversity and water tables.

A third conclusion is that if the C price increases over time to very high levels the conversion of reforested land back to agriculture production can be very costly. However, model-based analyses indicate that the value of bioenergy – and consequently the value of agricultural land – can, in a situation of very high C prices, become so high that it counter-balances the C cost of forest clearing for high-yielding bioenergy feedstock cultivation[143]. However, higher land values also imply higher food prices. Thus, even if some studies indicate a low risk that rising C prices lead to lock-in situations where land is locked under high-C forest sinks, it should be noted that ambitious climate targets might lead to increasing food prices caused by competition for land between C sinks, bioenergy and food.

CONCLUSIONS FOR POLICY MAKERS AND 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.

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 permitted 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. LUC effects depend strongly on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. Subsequently, implementation of bioenergy production and energy cropping schemes that follow effective sustainability frameworks and start from simultaneous improvements in agricultural management, could mitigate conflicts and allow the realisation of positive outcomes, e.g. in rural development, land amelioration and climate change mitigation including opportunities to combine with adaptation measures.

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.

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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 24 Members and is operating on the basis of 12 Tasks covering all aspects of the bioenergy chain, from resource to the supply of energy services to the consumer.

Further Information

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