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Carbon accounting of forest bioenergy

Conclusions and recommendations from a critical literature review

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Definitions

Aerosol	A collection of airborne solid or liquid particles (excluding pure water), with a typical size between 0.01 and 10 micrometers (μm) and residing in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in two ways: directly through scattering and absorbing radiation, and indirectly through acting as condensation nuclei for cloud formation or modifying the optical properties and lifetime of clouds.
Afforestation	The direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources.
Albedo	The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow covered surfaces have a high albedo; the albedo of soils ranges from high to low; vegetation covered surfaces and oceans have a low albedo. The Earth's albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.
Atmospheric carbon parity point	Net zero carbon emissions to the atmosphere by balancing the amount of carbon released with an equivalent amount sequestered or offset in comparison to the reference scenario
Biomass	Organic material both above ground and below ground, and both living and dead, e.g., trees, crops, grasses, tree litter, roots etc. Biomass includes the pool definition for above – and below –ground biomass.
Black carbon	Operationally defined aerosol species based on measurement of light absorption and chemical reactivity and/or thermal stability. Black carbon is formed through the incomplete combustion of fossil fuels, biofuel, and biomass, and is emitted in both anthropogenic and naturally occurring soot. It consists of pure carbon in several linked forms. Black carbon warms the Earth by absorbing heat in the atmosphere and by reducing albedo, the ability to reflect sunlight, when deposited on snow and ice.
Boreal forest	Forest that grows in regions of the northern hemisphere with cold temperatures. Made up mostly of cold tolerant coniferous species such as spruce and fir.
Branches	A division of a stem, or secondary stem arising from the main stem of a plant
Business as usual	The scenario that examines the consequences of continuing current trends in population, economy,

scenario	technology and human behavior.
Carbon dioxide equivalent	Carbon dioxide equivalent describes how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO2) as the reference.
Carbon neutrality	Net zero carbon emissions to the atmosphere during the energy production process (infrastructures excluded)
Carbon pool	A component of the climate system which has the capacity to store, accumulate or release carbon. Oceans, soils, atmosphere, and forests are examples of carbon pools.
Carbon Sequestration Parity	The moment in time when the bioenergy system has displaced the same amount of fossil C as would be absorbed in the forest if this was not harvested for bioenergy
Carbon stock	The absolute quantity of carbon held within a carbon pool at a specified time.
Climate change	The long-term fluctuations in temperature, precipitation, wind, and all other aspects of the Earth's climate. It is also defined by the United Nations Convention on Climate Change as "change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods".
Cropland	The land under temporary agricultural crops
Dead wood	Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground or in the soil. Dead wood includes wood lying on the surface, dead roots and stumps, larger than or equal to 10 cm in diameter.
Deforestation	The direct human-induced conversion of forested land to non-forested land.
Disturbances	Events including wildfires, insect and disease infestations, extreme weather events and geological disturbances, but not harvesting.
Fellings	Volume (over bark) of all trees, living or dead, above a 10 cm diameter at breast height, felled annually in forests or wooded land. It includes volume of all felled trees whether or not they are removed.
Forest	Land with tree crown cover (or equivalent stocking level) of more than 10 percent and area of more than 0.5 hectares (ha). The trees should be able to reach a minimum height of 5 meters (m) at maturity in situ. May consist either of closed forest formations where trees of various storeys and undergrowth cover a high proportion of the ground; or open forest formations with a continuous

	vegetation cover in which tree crown cover exceeds 10 percent. Young natural stands and all plantations established for forestry purposes which have yet to reach a crown density of 10 percent or tree height of 5 m are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest.
Forest management	Any activity resulting from a system applicable to a forest and aimed at improving any ecological, economic or social function of the forest
Forest residues	Tops, branches, bark, defective stems and other portions of trees produced as a byproduct during the normal course of harvesting stemwood as sawlogs, pulpwood or cordwood.
Forestry	The management of a forestland
Fossil fuels	Coal, oil, petroleum, and natural gas and other hydrocarbons are called fossil fuels because they are made of fossilized, carbon-rich plant and animal remains. These remains were buried in sediments and compressed over geologic time, slowly being converted to fuel.
Fossil fuel parity	The moment in time (the payback time) when the bioenergy system and the fossil reference have emitted the same amount of carbon
Fuel ladder	A firefighting term for live or dead vegetation that allows a fire to climb up from the landscape or forest floor into the tree canopy. Common fuel ladders include tall grasses, shrubs, and tree branches, both living and dead.
Global warming	Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere, which can contribute to changes in global climate patterns. Global warming can occur from a variety of causes, both natural and human induced. In common usage, “global warming” often refers to the warming that can occur as a result of increased emissions of greenhouse gases from human activities.
Global warming potential (GWP)	The global warming potential of a gas or particle refers to an estimate of the total contribution to global warming over a particular time that results from the emission of one unit of that gas or particle relative to one unit of the reference gas, carbon dioxide, which is assigned a value of 1.
Grassland	The land used permanently to grow herbaceous forage crops, either cultivated or growing wild.
Greenhouse gases	Greenhouse gases are those gaseous constituents of the

(GHG)	atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere.
Harvest residues	The wood usually left in the forest after stem wood removal, such as stem top and stump, branches, foliage and root.
Net Annual Increment	Average annual volume of gross increment over the given reference period minus mortality of all trees to a specified minimum diameter at breast height.
Ozone	Ozone (O3), the triatomic form of oxygen, is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (it is a primary component of photochemical smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, ozone is created by the interaction between solar ultraviolet radiation and molecular oxygen (O2). Stratospheric ozone plays a decisive role in the stratospheric radiative balance.
Radiative forcing	Radiative forcing is the change in the net vertical irradiance (expressed in Watts per square meter) at the tropopause due to an internal change or a change in the external forcing of the climate system, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun.
Salvage Logging Wood	Damaged, dying or dead trees removed due to injurious agents, such as wind or ice storms or the spread of invasive epidemic forest pathogens, insects and diseases or other epidemic biological risks to the forest, but not removed due to competition. Forest Salvage also includes wood removed to reduce fire hazard.
Sequestration	The process of increasing the carbon content of a carbon pool other than the atmosphere.
Short rotation forestry	The silvicultural practice under which high-density, sustainable plantations of fast-growing tree species produce woody biomass on agricultural land or on fertile but degraded forest land.
Sink	The rate of build-up of CO2 in the atmosphere can be reduced by taking advantage of the fact that carbon can accumulate in vegetation and soils in terrestrial ecosystems. Any process, activity or mechanism which removes a greenhouse gas from the atmosphere is

	referred to as a "sink".
Soil carbon	Organic carbon in mineral and organic soils (including peat) to a specified depth.
Stemwood	Wood from the main part of a tree; not from the branches, stump, or root. Salvage logging wood, thinnings, landscape care wood and other similar sources of wood that can be considered as by-products/residues are not included in this category of wood.
Stumps	The part of a plant and especially a tree remaining attached to the root after the trunk is cut
Sustainable Forest Management	The stewardship and use of forest lands in a way and at a rate that maintains their productivity, biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill now and in the future relevant ecological, economic and social functions at local, national and global levels and that does not cause damage to other ecosystems."
Thinnings	Trees removed during thinning operations, the purpose of which is to reduce stand density and enhance diameter growth and volume of the residual stand. Unacceptable growing stock which is defined as trees considered structurally weak or have low vigor and do not have the potential to eventually yield a 12 foot sawlog or survive for at least the next 10 years. Trees removed to reduce fire hazard are also included.

List of acronyms and Abbreviations

Acronym	Label
AFOLU	Agriculture, Forestry and Other Land Use
BAU	Business as Usual
BC	Black carbon
CHP	Combined Heat and Power
CN	Carbon Neutrality factor
CRF	Cumulative Radiative Forcing
EC	European Commission
EFSOS	European Forest Sector Outlook Study
FAO	Food and Agriculture Organization
FFSM	French Forest Sector Model
GHG	Greenhouse Gas
GWP	Global Warming Potential
HWP	Harvested Wood Products
iFUC	Indirect Fuel Use Change
iLUC	Indirect Land Use Change
iWUC	Indirect Fuel Use Change
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
LULUCF	Land Use, Land Use Change and Forestry
NAI	Net Annual Increment
NMVOC	Non Methane Volatile Organic Compound
NREAP	National Renewable Energy Action Plan
OC	Organic Carbon
RED	Renewable Energy Directive
SFM	Sustainable Forest Management
SRC	Short Rotation Coppice
SRF	Short Rotation Forestry
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change

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Executive summary

In the current European energy policy framework, biogenic CO_2 emissions from combustion of forest biomass used for energy and transport purposes are set to zero. Biomass is thus considered as a "carbon neutral" source (see definitions, pg 7). For this reason it currently appears that forest biomass is one of the most promising renewable resources in terms of climate mitigation impact, and thus it is likely to be widely exploited in the transport and energy sector. However, for some bioenergy pathways, (especially for dedicated harvest of stemwood for bioenergy purposes) this is more the result of static and incomplete accounting/reporting of carbon stocks flows rather than a physical reality.

The assumption of "carbon neutrality"[1] originates from the national greenhouse gas inventories of the United Nations Framework Convention on Climate Change (UNFCCC). The Intergovernmental Panel on Climate Change (IPCC) guidelines for the national greenhouse gas inventories estimate CO_2 emissions/removals from forestry based on changes in the carbon pools (live biomass, litter, soil, wood products). These are reported in the LULUCF[2] sector (Land Use, land-use change and forestry), independently from the end-use of such biomass. The carbon contained in biomass used for energy is reported as an emission in the year and at the point of harvest (when biomass is removed from the land). Therefore, in order to avoid double counting, the carbon emissions from biomass combustion are reported under the energy sector only as a memo item, and not added to the total energy sector emissions. This means that the total CO_2 emissions from the energy sector do not reflect emissions from the combustion of biomass, regardless of its actual value or the impact in LULUCF[3].

The carbon neutrality assumption is often used also in the assessment of the greenhouse gases (GHG) emissions of bioenergy in other contexts, even though the changes in the above mentioned forest carbon pools are not accounted for in those contexts, e.g., in the calculation of GHG emissions in Life Cycle Assessments (LCA) of bioenergy systems (and also in the LCA approach of the Renewable Energy Directive).

The "carbon neutral" accounting convention is applied in the case of annual crops and short rotation energy crops as the biogenic CO_2 emitted with the combustion is quickly reabsorbed by the next crop. However, in this case one should also consider possible release/sequestration of biogenic carbon due to direct land-use change, and whether these plantations are displacing crops already grown for food or feed (in which case the emissions due to indirect land use change must be included in the analysis) or take place in abandoned agricultural land (in which case a natural regrowth should be used as counterfactual in the fossil reference scenario).

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[1] There are many different definitions of "Carbon Neutrality" in literature. For the purposes of this report, "Carbon neutrality" occurs when the net carbon emissions from production and utilization of energy products is zero (infrastructure excluded)

[2] In the IPCC 2006 Guidelines for national greenhouse gas inventories, this sector was incorporated, together with "agriculture", under the new AFOLU (Agriculture Forestry and Other Land Use) sector.

[3] This *does not mean* that the IPCC Guidelines automatically consider biomass used for energy as "carbon neutral," as explained in Q 2-10: http://www.ipcc-nggip.iges.or.jp/faq/faq.html

In the case of dedicated harvest of stemwood for bioenergy purposes and short term GHG reduction policy objectives (e.g. 2020) the assumption of "carbon neutrality" is not valid since harvest of wood for bioenergy causes a decrease of the forest carbon stock, which may not be recovered in short time, leading to a temporary increase in atmospheric CO_2 and, hence, increased radiative forcing and global warming. At the local scale or stand level, the additional harvest of wood for bioenergy creates a temporary decrease of the carbon stock, compared to what would otherwise happen without harvesting. However, at the landscape or national level the mosaic of stands where forest biomass is removed for bioenergy has to be considered, and the continuous rate of wood removals could translate into a permanent decrease of carbon stock (or a lower increase compared to the reference fossil scenario).

Another important consideration that must be taken into account is that the combustion of woody biomass releases, in most cases, more CO_2 in the atmosphere, per unit of delivered energy, than the fossil fuels they replace. This is because biomass normally has less energy per kg of carbon and also lower conversion efficiency. Furthermore, higher energy losses and emissions are usually incurred in collecting, transporting, processing, storing and distributing the biomass fuel compared to traditional fossil fuels.

Therefore, if release of biogenic carbon is also accounted for, the bulk of the scientific literature suggests that all together these phenomena create an emission of biogenic-CO_2 from forest bioenergy which is, higher than the emissions from a reference fossil system in the short term (especially in the case of bioenergy dedicated harvest of stemwood). If the forest productivity increases because of the bioenergy production, the continuous substitution of fossil fuels may, in time, recover the additional emissions of bioenergy production. In these cases, at the payback time the fossil fuel parity is reached (i.e. the bioenergy system and the fossil counterfactual have emitted the same amount of CO_2 in the atmosphere). After the fossil fuel parity time, the bioenergy system starts to provide CO_2 savings.

Via a detailed analysis and review of the currently available literature, this work aims at clarifying the phenomena, physical and mathematical, underpinning the forest bioenergy carbon accounting and at compiling and assessing the methodologies and results reported so far. The scope of this report focuses on carbon fluxes, but other climate change impacts of forest bioenergy production are also mentioned. Other aspects such as: security of energy supply, socioeconomics, biodiversity, rural developments etc. are not dealt with in this report.

The reviewed studies indicate that the use of stemwood from dedicated harvest for bioenergy would cause an actual increase in GHG emissions compared to those from fossil fuels in the short-and medium term (decades), while it may start to generate GHG savings only in the long-term (several decades to centuries), provided that the initial assumptions remain valid. The harvest of stemwood for bioenergy purposes is not common today, however, it is becoming a more common practice that is expected to expand in the future.

The emissions increase of the forest bioenergy systems are more limited (in size and/or duration) with forest residues, thinnings and salvage logging (if not otherwise used for other purposes). For these feedstocks GHG savings are achievable in the short term (except for stumps in boreal climate, because of the very long time required for the natural decay). The GHG saving can be immediate if in the counterfactual scenario the wood would be burnt at roadside. This feedstock is expected to provide most of the

additional increment of biomass for bioenergy by 2020.

Also in the case of new plantations on agricultural or grazing land the GHG savings can be immediate (in absence of iLUC).

Waste wood and industrial wood residues, the most common feedstocks for pellets production as of today, provide GHG savings in the short term.

There is a large variability in the results of forest bioenergy fossil fuel parity times calculations. This large variability depends on the many different characteristics of the systems compared and non-consistent modeling assumptions and approaches. The first, most important assumption is on the fossil fuel displaced. Then, concerning both the bioenergy system and the reference fossil system the following characteristics heavily impact the results: efficiency in the final use, future growth rate of the forest, the frequency and intensity of biomass harvests, the initial forest carbon stock, the forest management practices assumed.

The timeframe of the comparison plays a relevant role also in the performances of the reference fossil system chosen for comparison. If the analysis timeframe is short, the current emissions from the reference system can be considered appropriate and constant. In the case of a long-term analysis, though, anticipated changes in the fossil reference system also have to be accounted for. For instance, in practically all of the studies analyzed, the fossil reference system (e.g. coal or natural gas) is kept constant and unchanged for the whole duration of the analysis (even centuries). However, the energy system will change in the future. It may change in one of the two directions: either towards decarbonization, implying that future savings might be much smaller than current ones, or towards more GHG-intensive fossil energy sources, implying a higher GHG saving. This should be adequately reflected in the reference scenarios. A further risk is that the land available for biomass harvest today may not be available (to the energy sector) long enough for the initial emissions to be compensated.

The land would provide important services also in the absence of using biomass for energy depending on the definition of the reference scenario. It could produce goods (food/feed/fiber) and/or could store/sequester carbon. For an adequate analysis, the economic and legal considerations in the reference scenario must deal explicitly with those services, i.e. their likelihood must be coherent with the assumed storyline of the reference scenario. Any change in the production level of these services caused by bioenergy production has to be allocated to the bioenergy scenario. Often, market mediated impacts of forest bioenergy are neglected or underestimated. Beside the displacement of raw materials from carbon intensive sectors (such as buildings), forest biomass for bioenergy might be sourced from other energy systems (such as industrial or energy sectors, household etc.), that consequently may have to replace it with fossil or more GHG intensive energy sources.

Furthermore it is common to compare a unit of renewable energy (including bioenergy and even energy savings from efficiency improvements) with a unit of fossil energy. However, because of the so called ‘rebound effect’, the substitution factor may be lower than 1. The rebound effect is the increased consumption of energy services following an improvement in the efficiency of delivering those services. This increased consumption may offset part of the energy savings that may otherwise be achieved.

Most of the studies assume that the productivity of the forest that follows the harvest does not change in the next rotation. However, increased bioenergy demand may lead (through market effects) to changes in forest management that could mitigate

the forest carbon losses (e.g. improved management, species with higher productivity, control and prevention of natural disturbances etc). However, being unpredictable events, it is complicated to include the occurrence of disturbances (fires, pest outbreaks and windthrow) in forest GHG savings potential calculation and distinguish the relative impact on the bioenergy and reference scenarios. Furthermore, after disturbances (for the wildfires depending on the severity) most of the biomass harvestable for bioenergy purposes would remain in the forest and can either be salvage-harvested or remain in the forest for decades. In any case large scale techno-economic quantitative studies effectively analyzing these market mediated mitigating impacts are not yet available.

A different reasoning needs to be applied to the displacement of wood used for products because these products generally require much less energy (and therefore GHG emissions) to be produced than their alternatives (concrete, metals etc.). Moreover, the wood carbon is stored in the products and it represents essentially another carbon pool. If wood resources were to be diverted from the wood products market to bioenergy, this additional pool would be reduced and additional emissions would result from the manufacture of substitute products. In the case of products, managing the forest determines higher GHG savings than suspending the management.

From the studies analyzed it emerges that in order to assess the climate change mitigation potential of forest bioenergy pathways, **the assumption of biogenic carbon neutrality is not valid under policy relevant time horizons (in particular for dedicated harvest of stemwood for bioenergy only) if carbon stock changes in the forest are not accounted for.**

Therefore, it is fundamental to integrate in the analysis all the carbon pools (above ground biomass, below ground biomass, dead wood, litter, soil and harvested wood products) and their evolution within the time horizon of the analysis for both the bioenergy and the reference scenario. The analysis and internalization of the market mediated GHG emissions (indirect Land Use Change, indirect Wood Use Change, indirect Fuel Use Change) is also of high importance. Moreover, a comprehensive evaluation of the climate impacts of forest bioenergy should also integrate all of the climate forcers (aerosols, ozone precursors and albedo), though agreed methods to include these are not yet available.

The challenges posed by the forest bioenergy sector and its influence on climate are exceptionally complex and differ between the short, medium and long-term perspectives, and thus require improved understanding. For a better understanding of the climate impact of bioenergy from forests at large scale (fundamental for policy assessment), the best approach would be to compare over time the overall climate effects of different policy scenarios. Ideally, a model is needed capable of simulating the temporal dynamics of GHG emissions and removals for all the following impacts of a bioenergy policy: carbon stock changes in the forest (i.e. increase in carbon stock); carbon stock changes outside the forest (i.e. increase of the harvested wood products pool), material substitution effects and energy substitution effects.

Such a model should be capable of simulating the impact of different management options on forest growth at EU level for at least few decades, including all the carbon pools and the risks associated with natural disturbances. Sound links with specific market models (i.e. to consider the demand of specific products) and with a macroeconomic global model (i.e. to include the impact of import and exports from outside EU) are also needed. In the medium term, the representation of other relevant climate forcers (long-lived GHG, short-lived GHG, aerosols and albedo,

evapotranspiration) would also be useful. Then, by comparing different scenarios, and depending on different aims and temporal perspectives, policy makers may take informed decisions on what is the best use of forested land.

In order to develop a common, comprehensive and scientifically sound methodology for the assessment of the climate impacts of bioenergy, future research required to provide more background data (especially on indirect impacts) and the reduction of uncertainties in the climate impacts of other forcers than CO_2.

1. Introduction

1.1. Background

At the end of 2010, in the context of the United Nations Framework Convention on Climate Change (UNFCCC), it was recognized that global warming must not exceed the temperatures experienced before the industrial revolution by more than 2° C. This is considered to be vital if the negative consequences of human interference with the climate system are to be limited. This long-term goal requires global greenhouse gas emissions to be reduced by at least 50% below 1990 levels by 2050. Developed countries as a group should reduce their emissions by 80 to 95% by 2050 compared to 1990 levels *[COM(2012) 94]*.

To kick-start this process, the EU Heads of State and Government have set a series of demanding climate and energy targets to be met by 2020, known as the so called "20-20-20" targets. These goals consist of:

- A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels;
- 20% of EU final energy consumption to derive from renewable resources;
- A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

In January 2008 the European Commission (EC) proposed a binding legislation to implement these targets. The Directive 2009/28/EC (Renewable Energy Directive - RED) *[RED 2009],* addresses various subjects related to the development of renewable energies in the European Member States, among others, the legally binding share of renewable energy in gross final energy consumption. In Article 4 of the Directive each Member State is requested to provide to the EC a National Renewable Energy Action Plan (NREAP). According to the plans presented, by 2020 41 Mtoe of the European primary energy supply (out of 244 Mtoe for all the renewables) is forecasted to come from biomass obtained directly from forestry *[Beurskens 2011]*.

In order to guarantee not only an increased use of bioenergy but also a sustainable one, the RED includes specific, mandatory sustainability criteria for biofuels and bioliquids. Among them, a minimal threshold of GHG savings is defined, as well as a simplified methodology for the calculation of the GHG emissions. The EC recommended to Member States to introduce national sustainability schemes also for solid and gaseous biomass used in electricity, heating and cooling *[COM(2010) 11]*. The recommended rules were aimed to be as consistent as feasible with those given in the RED for biofuels.

The methodology defined to calculate GHG savings includes all emissions from the extraction or cultivation of raw materials, emissions from processing, transport and distribution and annualized emissions from carbon stock changes caused by direct land-use change. In the RED, the emissions of biogenic CO_2 from the fuel in use are set to zero, considering the biofuels carbon neutral. This assumption is commonly accepted for annual crops, short-rotation coppices and agri-residues, wood waste and industrial wood residues as the carbon emitted will be sequestered again within a short timeframe, compared to the situation where such biomass is left in the agro- or forest system to decay naturally (although there may be an impact on soil carbon balance). But in the case of forest bioenergy (especially stemwood), the carbon emitted from combustion can actually spend a long time in the atmosphere before being recaptured through biomass growth. Basically, the RED methodology ignores any change in the carbon stock

on land if it does not involve LUC (e.g. if the forest remains a forest, regardless how much the carbon stock was reduced). It also ignores the displacement of products and services the land would produce in the absence of biomass production.

Depending on the specific characteristics of the forest system under analysis, the fossil fuel replaced and the timeframe of the analysis, the bioenergy system might result in GHG emissions higher than those from the fossil system. Recently published studies *[Cherubini 2011; Holtsmark 2010; Johnson 2009; Mitchell 2012; Pingoud 2012; Schulze 2012; Searchinger 2009; Zanchi 2011]* argue that in the dedicated harvest of stemwood for bioenergy is counterproductive to reach short term GHG emission reduction targets. Also other reviews *[Helin 2012, Bowyer 2012, Lamers 2013a]* and position papers or regulations *[EEA 2011, Shultze 2012, EPA 2012]* recognize the limits of using the carbon neutrality assumption for forest bioenergy. In particular the Massachussetts renewable energy portfolio standard regulation *[Massachussets 2012]* does not consider bioenergy dedicated harvest of stemwood eligible as renewable energy source.

However, currently, forest biomass is still often considered inherently carbon neutral, (and the others climate forcers are not accounted for), making it one of the most promising renewable resources in terms of climate mitigation impact and thus likely to be largely exploited for bioenergy.

1.2. Scope of this review

The aim of this review is to analyze the climate impact of forest bioenergy by reviewing in detail the most up–to–date information on the subject in terms of modeling approach and techniques, data availability, results and conclusions achieved by the international scientific community and published in relevant peer-reviewed journals or by internationally recognized institutions.

However, stimulating bioenergy production affects many other aspects such as security of energy supply, socioeconomics, biodiversity, rural developments etc. that are not dealt with in this report.

The review will introduce the main physical phenomena underpinning the forest bioenergy carbon accounting through the results available in the literature, and will try to quantify the possible contribution of forest bioenergy pathways to the achievement of the climate policy targets.

The concept of "carbon debt" has different interpretation in literature *[Bowyer 2012]*. For example Walker *[Walker 2010]* defines it as the 'additional carbon emission over the fossil system'. Some sources refer to it as the 'loss of carbon stock in the forest' (e.g. in Matthews et al. *[Matthews 2012]*). However, given the misunderstanding that the use of this definitions may generate, the term 'carbon debt' is not used in this analysis.

The term 'bioenergy system' is used to define the scenarios in which the production of energy is achieved with forest biomass combustion. In the papers and reports reviewed this system is compared to a fossil 'reference system' (sometimes called 'counterfactual') in which the energy is produced with fossil energy sources. These scenarios are defined by the authors of the works reviewed (e.g. in terms of type of biomass/fossil fuels used, processing, final utilization etc.). Therefore, there is not a single consistent scenario used throughout the report. These inconsistencies in the scenarios definitions (especially on the boundaries and assumptions) are analyzed and taken into account in order to provide recommendations on how to set proper analysis

boundaries and reasonable assumptions in future studies.

Section **Error! Reference source not found.** introduces and explains the specific issues relates to the forest carbon accounting and their origins in the incomplete accounting of carbon pools.

Chapter **Error! Reference source not found.** expands on the methodologies used to quantitatively assess the effects of using forest wood for bioenergy on the carbon cycle and climate. It also analyses the importance of the assumptions and boundaries (temporal and spatial) definition.

Chapter 3 analyses the forest bioenergy climate impacts due to other climate forcers than CO_2.

Chapter 4 identifies the market mediated climate impacts of forest bioenergy incentivisation and focuses on more 'consequential' effects.

Finally, Chapter 5 indicates the research needed in order to have more appropriate data and tools to include proper climate impact assessment in forest bioenergy LCAs and policies.

1.3. Problem definition

It is important to understand the carbon cycle in order to develop a view on the climate change mitigation of bioenergy. The earth has five principal carbon pools *[Berndes 2011]* – fossil resources, the atmosphere, the ocean, the biosphere (all ecosystems) and the pedosphere, (the free layer or soils above the bedrock). There are large bi-directional flows between the atmosphere and the biosphere, which are difficult to quantify, while the flows from the fossil pool to the atmosphere are well quantified. Part of the C that is emitted in the atmosphere is absorbed by the ocean and the biosphere due to reforestation *[Berndes 2011]*.

In the current European renewable energy policy framework, forest biomass used for energy and transport is considered as a carbon neutral source, thus, the carbon flow between the biosphere and the atmosphere is neglected.

The assumption of "carbon neutrality" originates from the national GHG inventories of the United Nations Framework Convention on Climate Change (UNFCCC). The Intergovernmental Panel on Climate Change (IPCC) guidelines for the national GHG inventories estimates CO_2 emissions/removals from land based on changes in the carbon pools (biomass, soil, wood products). These are reported in the LULUCF[4] sector (land use, land-use change and forestry), independently from the end-use of such biomass. The carbon contained in biomass used for energy is reported as emission at the point of harvest (where biomass is removed from the land). Therefore, to avoid double counting, the carbon emissions from biomass combustion are reported under the energy sector only as a memo item, and not added to the total energy sector emissions. This means that the total CO_2 emissions form the energy sector do not reflect emissions from the combustion of biomass, regardless of its actual value or the impact in LULUCF.

This approach is valid for national GHG reporting, provided that the land use sector is fully reported, a condition explicitly recognized by the IPCC. However, it is often applied out of its original context to the assessment of the GHG performances of

[4] In the IPCC 2006 Guidelines for national greenhouse gas inventories, this sector was incorporated, together with "agriculture", under the new AFOLU (Agriculture Forestry and Other Land Use) sector.

bioenergy, (e.g. in Life Cycle Assessments - LCA) even in cases where there are no provisions for accounting land use emissions, i.e. ignoring the resulting changes in other carbon pools.

In case that there is no raw material displacement from other sectors such as food, feed, fibers or changes in land carbon stocks due to direct or indirect land use change, the assumption of carbon neutrality can still be considered valid for annual crops, agri-residues, short-rotation coppices and energy grasses with short rotation cycles. This can also be valid for analysis with time horizons much longer than the feedstock growth cycles.

But in real life situations, the land could provide important services also in the absence of using biomass for energy. It could produce goods (food/feed/fiber) and/or would store/sequester carbon, in particular in the case of high carbon stocks (forest biomass) and short term GHG reduction policy objectives (2020) the bioenergy carbon neutrality assumption is not correct *[EEA 2011, Bowyer 2012]*.

For example, if wood from a 90 years old boreal forest stand is harvested and combusted, its carbon is released in a pulse but it will only be fully re-absorbed by the re-growing forest approximately in the next 90 years. The effect on the climate of such CO_2 persistence in the atmosphere through its radiative forcing should thus not be neglected and be taken into account in bioenergy LCAs.

Forests consist of a complex series of six carbon pools[5] constantly interacting among each other, as described thoroughly in the IPCC Guidelines *[IPCC 2006]* in which the amount of carbon stored in an old–growth, unmanaged forest would represent the theoretical maximum.

However, when a forest is actively managed, it actually generates products (other services are not considered in this report), most commonly timber for furniture and building materials, pulp for paper production, and bioenergy from residues.

Examples of forest management scenarios are reported in Matthews et al. *[Matthews 2012].* In their work they have estimated the absolute GHG emissions for characteristic UK forest types involving management for production of wood for a range of materials and fuel.

Their example for managed coniferous forests involves production of a combination of sawn timber, medium-density fiberboards (MDF), paper and card and woodfuel, the latter being branches and bark used for commercial and industrial CHP generation with wood chips. As generally paper and card are not produced from hardwoods in the UK, the equivalent scenario for broadleaf forests is slightly simpler, involving the production of sawn timber, MDF and woodfuel for CHP.

[5] The six pools are: a) above ground biomass ; b) below ground biomass ; c) dead wood ; d) litter ; e) soil and f) harvested wood products (HWP)

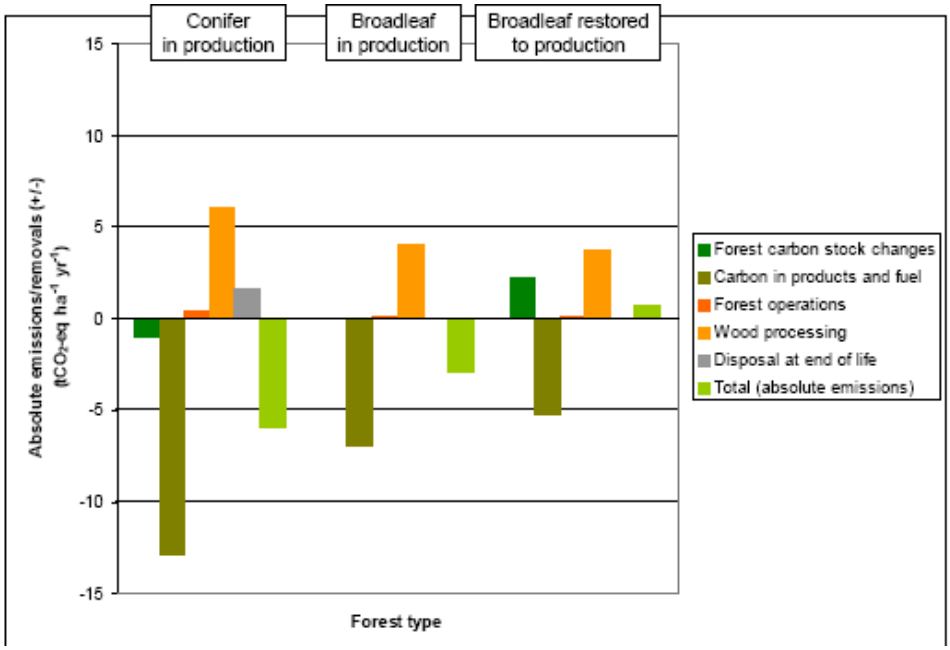

Figure 1: Absolute GHG emissions estimated for characteristic UK forest types for example scenarios involving management for production of wood for a range of materials and fuel. Total emissions are shown as well as contributions to the total due to forest carbon stocks, carbon in harvested wood, forest operations and wood processing including combustion. Results are shown for 40 year time horizon. *[Matthews 2012].*

Error! Reference source not found. shows the total emissions as well as the contributions to the total due to forest carbon stocks, carbon in harvested wood, forest operations and wood processing (including combustion). The time horizon of the analysis is 40 years. The total emissions are negative, therefore the use of UK wood for material production (light green bar, –6.0 tCO_2-equivalent/ha*yr for coniferous forests in production) results in a carbon sink.

Applying the same methodology to the use of wood for fuel only the study finds that net emissions are very close to 0 (slightly positive for broadleaf in production, slightly negative for conifers) in the same timeframe of 40 years (**Error! Reference source not found.**).

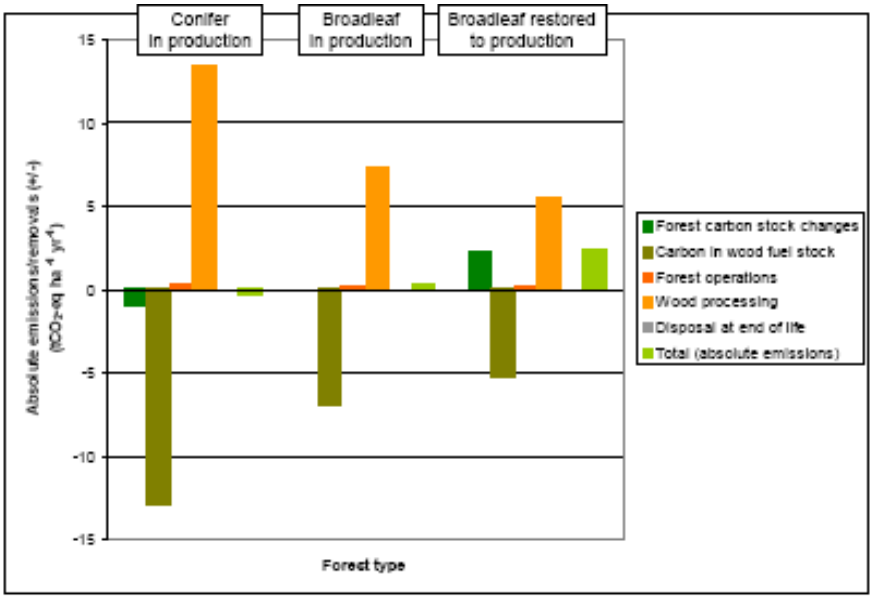

Figure 2: Absolute GHG emissions estimated for characteristic UK forest types for example scenarios involving

management for production of wood for fuel only (Scenario 01.06, without application of CCS). Total emissions are shown as well as contributions to the total due to forest carbon stocks, carbon in harvested wood, forest operations and wood processing including combustion. Results are shown for 40 year time horizon. . *[Matthews 2012].*

In order to assess the relative emissions of both scenarios (wood for fuels or materials), counterfactual scenarios were defined based on assumptions about the most likely displacement options. In the case of materials, the counterfactual corresponds to the amount of materials and energy (from non-wood sources or from imported wood in the case of paper) equivalent to that produced using the raw wood from 1 ha of forest (**Error! Reference source not found.**). For the energy only scenario the counterfactual is based on UK grid average electricity (**Error! Reference source not found.**).

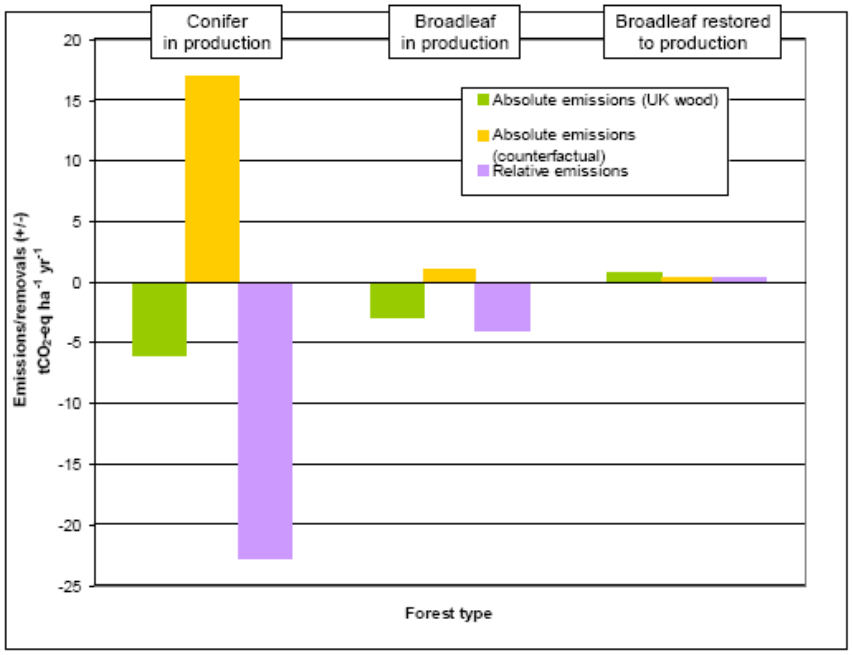

Figure 3: Estimation of relative GHG emissions for characteristic UK forest types for example scenarios involving management for production of wood for a range of materials and fuel. Absolute emissions are shown for production from UK forests, for a counterfactual scenario as well as the resultant relative emissions. Results are shown for 40 year time horizon

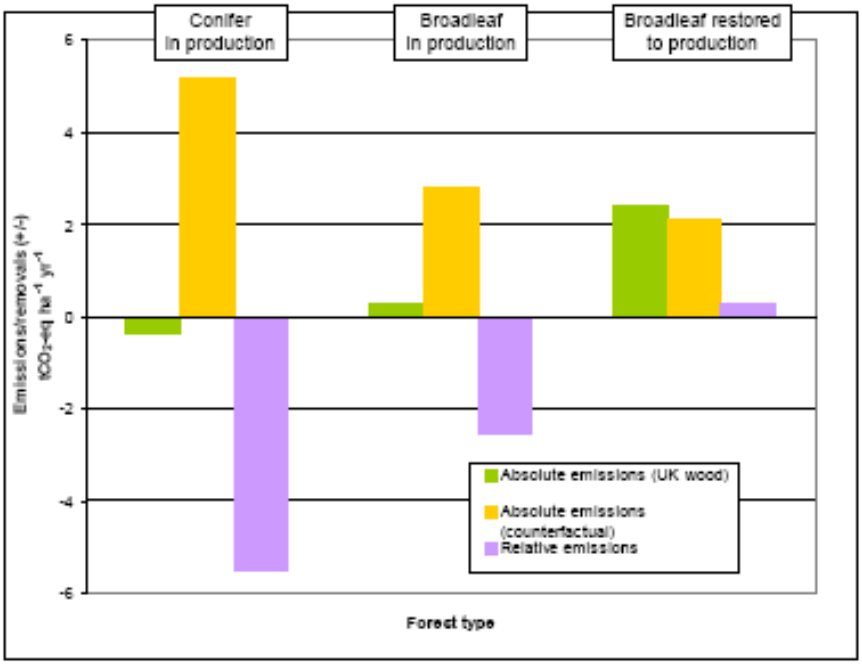

Figure 4: Estimation of relative GHG emissions estimated for characteristic UK forest types for example scenarios

involving management for production of wood for fuel only (in this case power only). Absolute emissions are shown for production from UK forests, for a counterfactual scenario as well as the resultant relative emissions. Results are shown for 40 year time horizon

The counterfactual scenario has to include also the carbon sink due to the suspension of the management of the forest. The results are shown in **Error! Reference source not found.**.

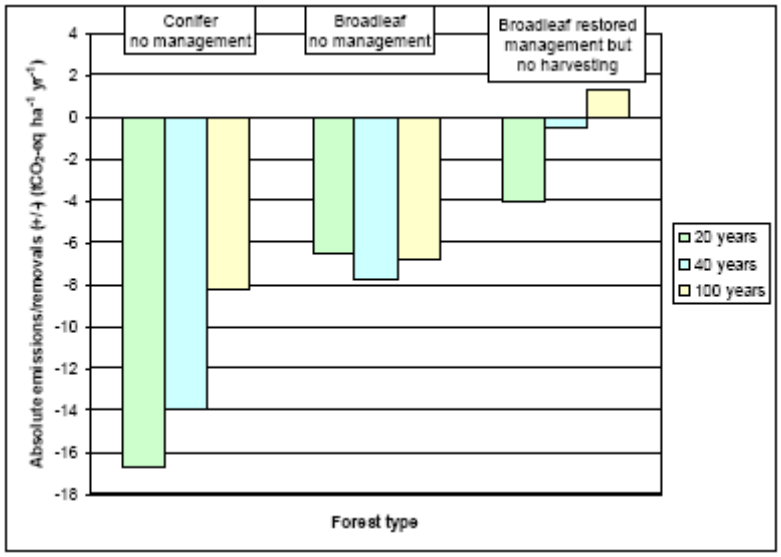

Figure 5: Rates of carbon sequestration (or emissions) estimated for characteristic UK forest types when management is suspended. Results are shown for time horizons of 20, 40 and 100 years.

Using as example the coniferous forests under production, it is possible to calculate the GHG performances of the two scenarios (wood for energy and wood for materials) in comparison to the counterfactual (given in Fig.5) in a 40 years timeframe.

In the case wood is used for bioenergy only the total emissions of the bioenergy system would be -5.5 tCO_2/ha*y (5.1 tCO_2/ha*y from displacement of fossil fuel and 0.4 tCO_2/ha*y due to the sink of the forest system), that, compared to the missed growth of the forest (14 tCO_2/ha*y) results in net emissions of 8.5 tCO_2/ha*y. **This result shows that, in a 40 years timeframe, CO2 emissions are lower for the suspended management forest than for the forest managed for bioenergy only**. The second case is if the wood is used for materials as well as bioenergy (bioenergy from residues). In this case the total emissions of the material and bioenergy system would be -22.8 tCO_2/ha*y, (-6 tCO_2/ha*y in carbon stock of the forest and products and –16.8 tCO_2/ha*y from displacement of products) to which the missed growth of the forest has to be subtracted (14 tCO_2/ha*y) resulting in net GHG savings of 8.8 tCO_2/ha*y. **Therefore managing the forest for products determines higher GHG savings than suspending the management.**

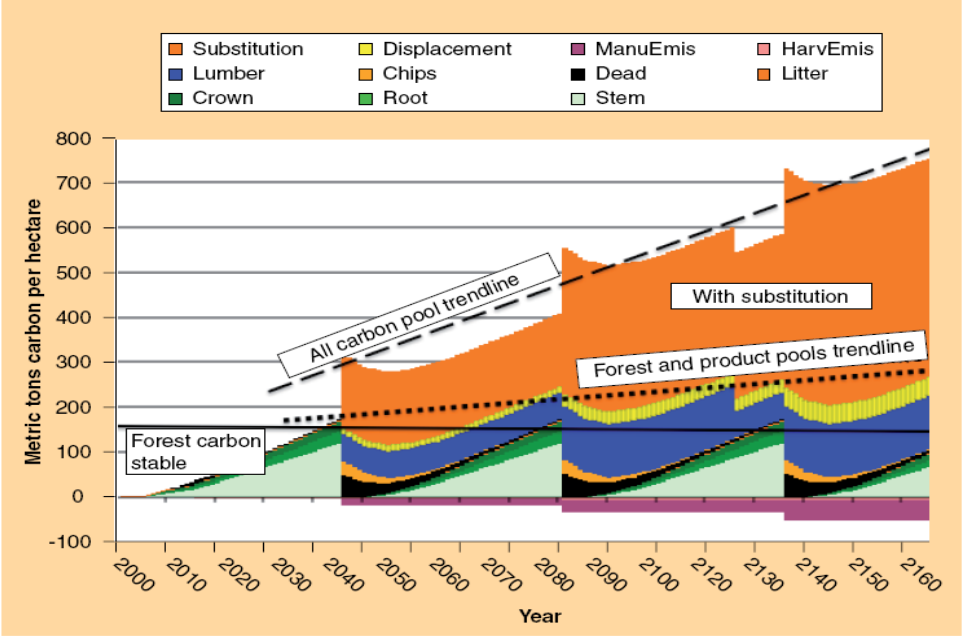

Figure 6: Total carbon pools: forest, product, emissions, displacement and substitution. The substitution benefit of using long-lived wood products provides the greatest carbon leverage of all pools, adding to the forest, products and displacement pools less any processing emissions that are incurred in production. Soil carbon (not shown) would increase the total forest contribution to this carbon profile, but under sustainable management regimes, shows no significant change from rotation to rotation. Source: *[Lippke 2011]*

Error! Reference source not found. shows how the carbon pools evolve with time in a wood for materials modeling case for the Pacific North West region of the U.S. *[Lippke 2011]*.

If harvesting for bioenergy increases the productivity of the forest compared to what it would be in the reference system, the continuous substitution of fossil fuels will eventually compensate for the carbon stock change in the forest due to the new management. It will take then several years, decades or even centuries before the advantages of using wood for bioenergy become apparent (provided that many assumptions remain valid), as it will be described more in details in the next sections.

2. Carbon accounting for forest bioenergy

There is a general agreement in the scientific *[Cherubini 2010]* and policy community *[RED 2009]* that Life Cycle Assessment (LCA) is the best methodology for the GHG balance calculation of bioenergy systems.

LCA is a structured, comprehensive and internationally standardized method. It aims to assess all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services ("products").

LCA takes into account a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste. Critically, LCA studies thereby help to avoid resolving one environmental problem while creating others. This unwanted "shifting of burdens" is where you reduce the environmental impact at one point in the life cycle, only to increase it at another point.

In line with the reviewed papers, this work focuses only on climate change impacts. Therefore the LCA potential of analyzing the tradeoffs among different impact categories is not fully exploited (impact categories such as toxicity, eutrophication, acidification etc. are not analyzed).

The attributional life cycle inventory modelling principle depicts the potential environmental impacts that can be attributed to a system (e.g. a product) over its life cycle, i.e. upstream along the supply-chain and downstream following the system's use and end-of-life value chain. In attributional modelling the system is hence modelled as it is or was (or is forecasted to be) and includes all the processes that are identified to relevantly contribute to the system being studied. *[ILCD 2010]*. In attributional LCA if among the systems to-be-compared, one or more systems have additional functional units, comparability shall be achieved by system expansion *[ILCD 2010]*.

In simple words, in order to be comparable, the two systems have to provide the same level of products or services; therefore the system under analysis is expanded to include additional services/products in order to equal the system to which it is compared to. This is fundamental when wood products are accounted for in the analysis. The wood used for energy purposes might be used (or was used) to replace products that often are more GHG intensive (cement, metals) or that, in any case would retain the carbon out of the atmosphere longer (see Section **Error! Reference source not found.**). The LCA approach can be tailored to specific geographic conditions and can thus give a very specific and precise picture of the effects of different management techniques on the forest carbon pools.

Given the numerous methodological choices and assumptions that have to be made while performing an LCA, the results of GHG balances can differ significantly even for apparently similar systems. In the following sections the main peculiarities and results of forest bioenergy GHG LCA methods and indicators are analyzed.

2.1. Forestry models & payback time calculation

2.1.1. Bioenergy dedicated harvest of stemwood

As regards stemwood from additional harvest for energy purposes only, several examples are already available in the international literature. Often, as indicator, the fossil fuel parity time is calculated. The fossil fuel parity time is the time required by the bioenergy system to reach the same carbon emissions to the atmosphere as the reference fossil system. From that moment on, the bioenergy system starts to deliver GHG savings.

The calculations are based on the fact that when a forest is harvested at regular intervals, even if a sustainable management (SFM) is in place and the removed amount is kept lower or equal to the Net Annual Increment (NAI), the total carbon stored in the forest will increase in time (in absolute terms) or stay stable in value but at a level lower than that one for an unmanaged forest *[Holtsmark 2010; Holtsmark 2012a; Lippke 2011; Malmsheimer 2011; McKechnie 2011]*.

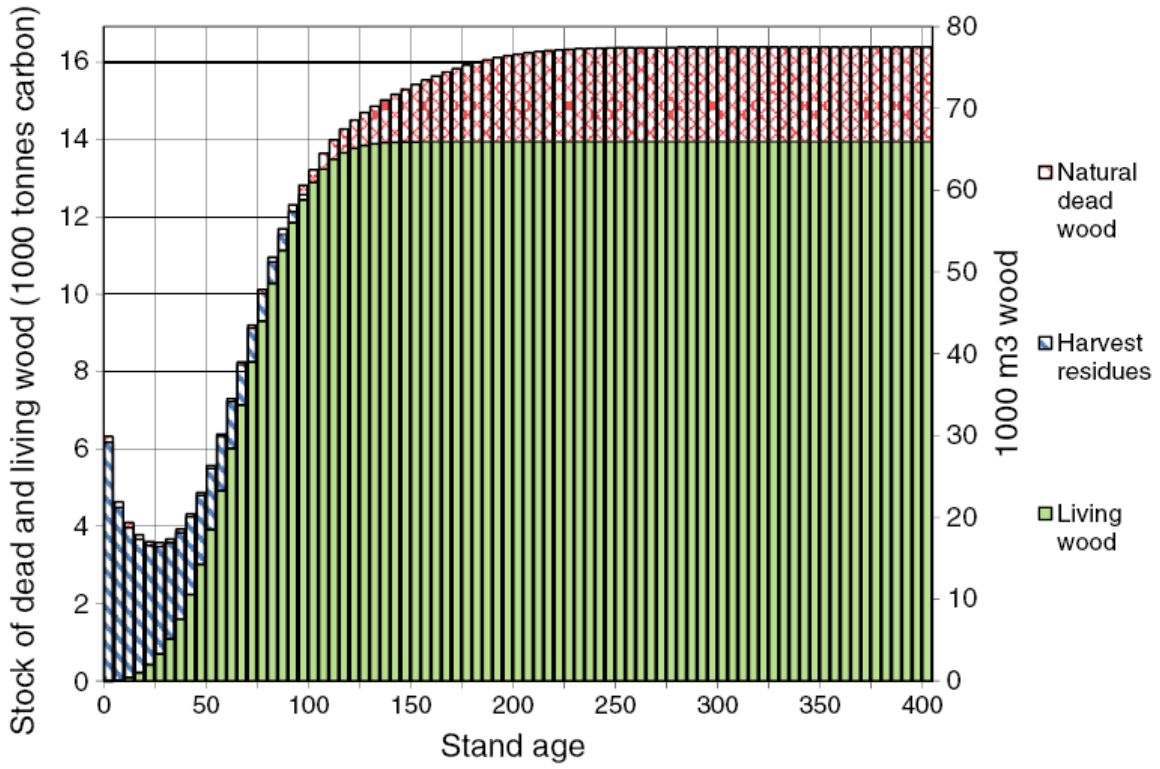

Figure 7: Development of the volumes of wood pools in a forest parcel : living wood, harvest residues and natural deadwood after clear-cutting and replanting in the standard parcel. Stand age at time of last felling was 95 years. Source: *[Holtsmark 2012a]*.

An example of growth curve for a stand of boreal forest harvested at year 0 is reported in **Error! Reference source not found.**. The initial clearcutting introduces large amounts of biomass into the ground, which results in the forest being a source of CO_2 for many years or even decades after the disturbance *[Janisch 2002; Kowalski 2004, Trømborg 2011]*. Kolari *[Kolari 2010]*, who studied a stand clearfelled 4 years before with Scots pine and of medium fertility, concluded that it was a source of approximately 400 gC m^{-2} per year.

In boreal forests, for example, 70–120 years are necessary before a stand of trees is mature; in temperate or tropical forests this time is normally shorter (depending on the

species and site conditions) but the growth curve has a similar shape.

For illustrative purposes, managed forests can be represented by assuming a site specific rotation length between harvests by clearcutting, followed by regeneration and ignoring thinnings. As it is evident from **Error! Reference source not found.**, harvesting at regular intervals guarantees an average constant carbon stock in the stand and in the forest. However this amount is lower than the carbon that would be stocked if no harvest was applied (natural regrowth) or if longer rotation cycles were used.

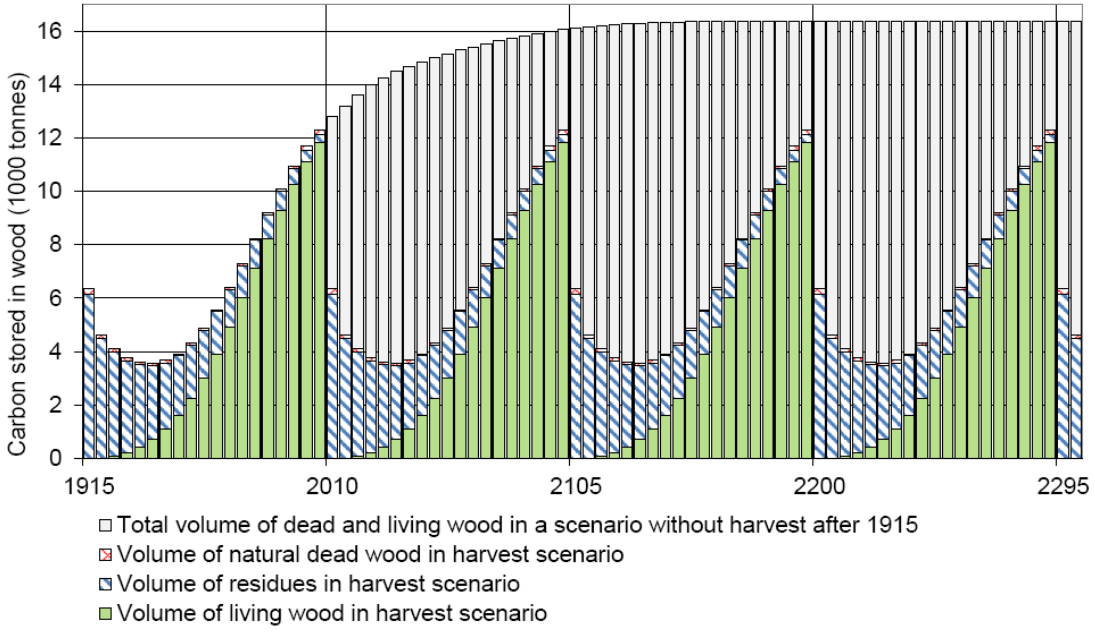

Figure 8: Development of carbon stock in dead and living wood in a parcel with and without harvest. The case with clear-cutting for years 2010, 2105, 2200 and 2295, and without harvest after 1915. Source: *[Holtsmark 2012a]*.

Considering all the parcels in a forest, it is possible to calculate the effect of the choice of the rotation time on the amount of carbon stored in the forest pools of carbon (living wood, harvest residues and dead wood) and the amount of wood to be felled annually to keep constant the rotation time. For example: if 100 hectares with a rotation time of 100 year are considered, then a hectare per year has to be harvested, with a rotation time of 50 years, two hectares per year are harvested.

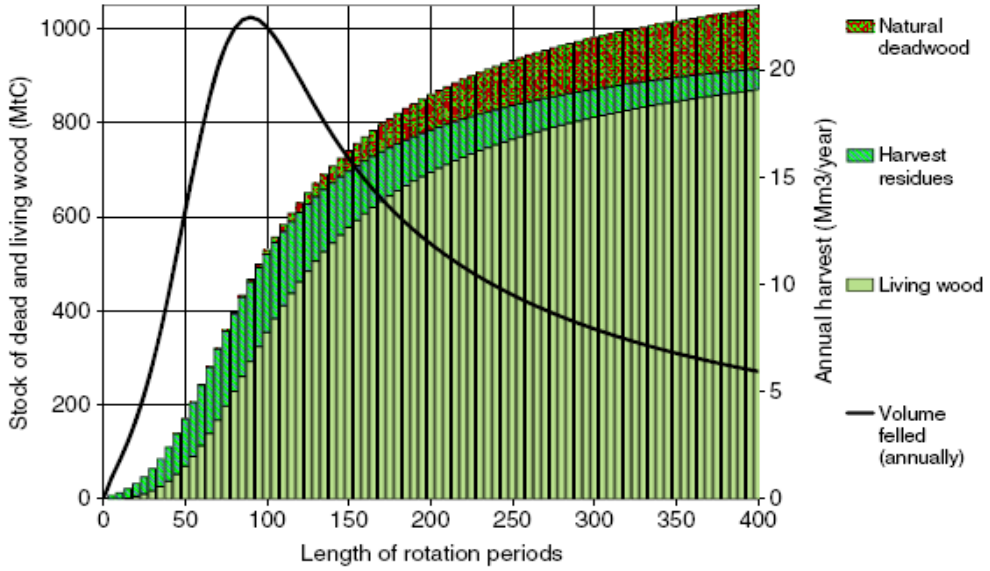

Figure 9: Total carbon stock for an entire forest depending on the length of harvesting rotation periods. Annual volume of timber felled (black curve) and quantity of carbon stored in dead and living wood (columns) at different steady states for harvesting rotation cycles of different lengths. Source: *[Holtsmark 2012a]*.

Error! Reference source not found. shows that shortening the rotation time decreases the amount of carbon stored in the forest to a new, lower, steady level, whatever the use of the harvested biomass is. If the current rotation is longer than that corresponding to the culmination of the harvest rate (in this case 90 years), shortening the rotation time may increase the average annual harvestable volume. Therefore, the lowering of the carbon stock will be compensated over time by the increased accumulated production volumes (and therefore substitution benefits).

The biggest productivity would be achieved at a rotation length corresponding to the culmination of the annual harvest. If the rotation is shortened to an extent for which the productivity decreases, the initial additional emissions of the bioenergy system cannot be paid back as either less woody materials or less bioenergy are produced, and therefore the substitution credits are absent.

This approach, the additional harvest, is often chosen in order to apply the attributional modeling. If, instead of modeling the additional harvest, the management is kept constant, but instead of products the wood is used for bioenergy, the effects of the displacement of wood for products should be internalized in the analysis, and again, the materials replaced by wood being normally more GHG intensive, the are no savings that can, with time, repay the carbon stock change in the forest. If the wood for material would not be produced because of lack of market demand, then the counterfactual should be the suspended management of the forest.

Moreover, the largest long term GHG benefit does not always correspond to the highest productivity of the forest. The choice of a rotation length longer than the culmination point may lead to the production of material with higher substitution factors (e.g. wood for building materials instead of pulpwood) therefore to an increased GHG benefit *[Pingoud 2010]*.

If the harvested wood is combusted to produce energy, then the carbon content of the wood is released in a pulse, in the year of harvest, as CO_2. The forest, growing year by year, will reabsorb the CO_2 emitted. If the energy content of the biomass is used to replace fossil fuel, the emissions avoided by substitution contribute to recover the initial CO_2 emissions, as shown by **Error! Reference source not found.** for a single parcel.

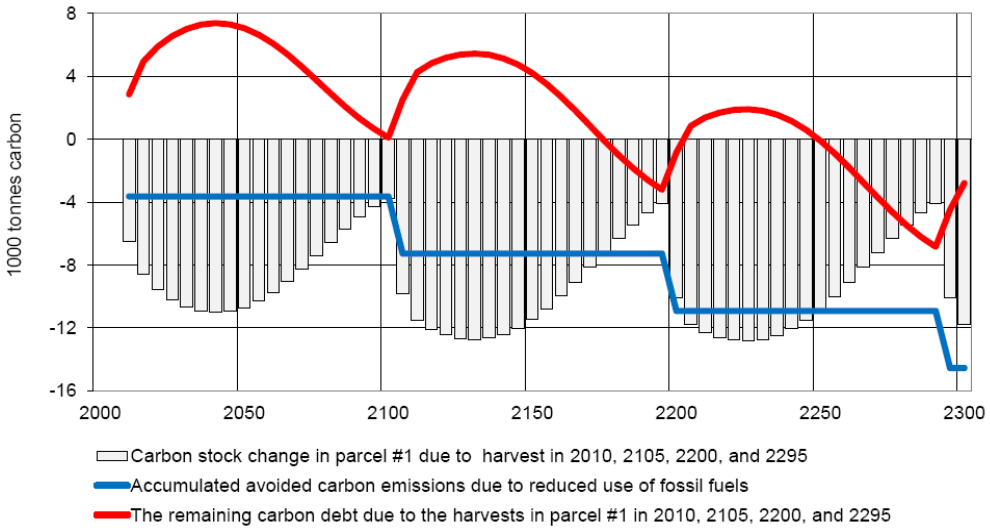

Figure 10: Consequences of continuous harvest in a forest parcel on its carbon stock, the accumulated reduction in fossil carbon emissions and the remaining carbon debt (Holtsmark defines the carbon debt as the additional emissions over the fossil system). Source: *[Holtsmark 2012a]*.

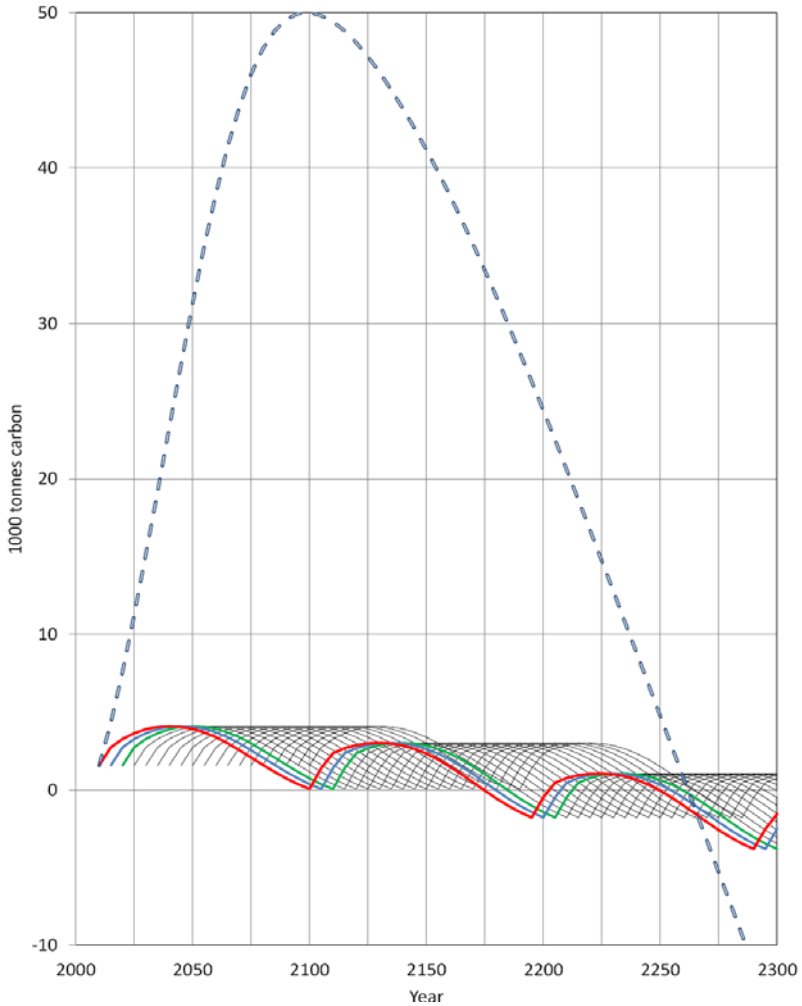

Figure 11: Cumulative carbon debt for continuous harvest on a whole forest. The multi-wave-shaped curves show the development of the remaining carbon debt generated from the harvesting of 19 parcels as they subsequently mature. The total remaining carbon debt is given by the dotted blue curve(Holtsmark defines the carbon debt as the additional emissions over the fossil system). Source: *[Holtsmark 2012a]*.

Adding up all the parcels of a forest and considering a status of continuous harvest results in a multi-wave-shaped curve, where each individual curve is time delayed and all the curves are summed. The total remaining bioenergy initial additional emissions over the fossil system is given by the dotted blue curve in **Error! Reference source not found.**. The cumulative effects of continuous harvest are reported also in Holtsmark *[Holtsmark 2012b].*

It has to be noted also that, once the fossil fuel parity time is reached, the bioenergy system still has contributed to global warming more than the fossil fuel system. In that precise moment in time the cumulative emissions of the fossil and bioenergy systems are the same. However, the bioenergy system would have had higher GHG emissions until that moment, leading to higher radiative forcing till the fossil fuel parity is reached (payback time).

Error! Reference source not found. illustrates the payback time concept: the difference between the green and the black line till the fossil fuel parity is reached, represents the additional emission over the fossil fuel. The atmospheric carbon parity point (the point in time when bioenergy may be considered carbon neutral) would not be reached until the additional emissions are saved by substituting fossil fuels combustion. At the moment in time when the savings (L1) equal the emissions due the additional harvest (L2) the atmospheric carbon parity point is reached. It needs to be noted that atmospheric carbon parity point does not necessarily mean climate neutrality since GHG emissions happen at the beginning of the process while savings at the end and their effect on climate are different.

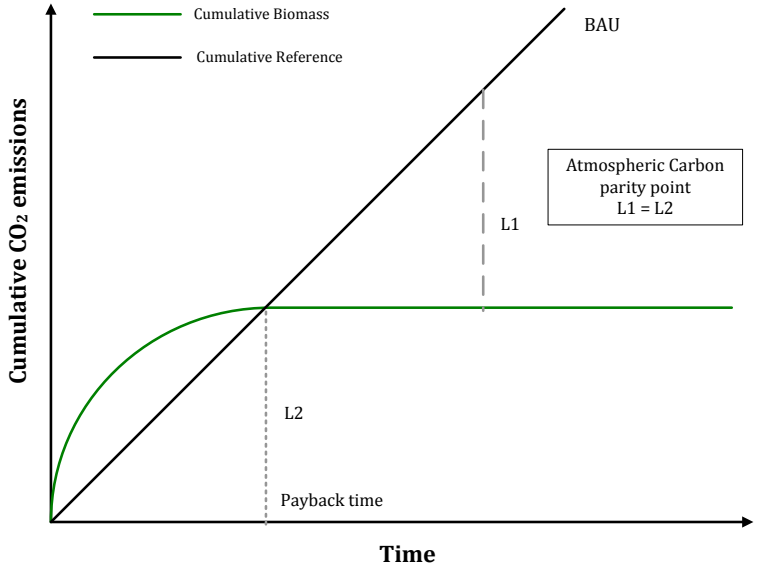

Figure 12: Visual description of payback time and atmospheric carbon parity point. Green Line: drop in the forest carbon stock due to bioenergy production; Black line: accumulated reduction in carbon emissions from substitution of fossil fuels

The issue of higher initial CO_2 emissions does not apply only to the clear-cut of forest parcels, but also to thinning practices and residues. In fact also increased harvests by more frequent or increased thinning causes a reduction of the carbon stock of the forest (that can be mitigated by the faster growth of remaining stems). Residues harvest instead causes a reduction in the respective forest carbon pool.

What happens to the forest in terms of carbon stock changes has to be accounted for in both the bioenergy and fossil scenarios *[Mitchell 2012]*.

The examples reported so far consider the case of forest carbon stock changes due to additional harvest and use of the increase forest production for bioenergy.

However the wood for bioenergy may be sourced from unmanaged forests or from forests previously managed for wood products. In the first case clearly the fossil system should account for the carbon that would be stored in the unmanaged forest. In the second case there would not be a carbon stock change in the forest, but, either the wood products would have to be produced with wood from another forest (causing an indirect carbon stock change) or replaced with other materials, normally by far more GHG intensive (e.g. concrete, metals etc., see **Error! Reference source not found.**) or, if they are not anymore needed (e.g. because of an economic downturn) the reference scenario should include the natural regrowth of the forest.

Error! Reference source not found. summarizes the results of this literature review on payback times as regards bioenergy dedicated stemwood harvest.

The reviewed studies show payback times ranging from 0 to almost 500 years. This large variability depends on the many different characteristics and assumptions on both the forest/bioenergy system and the reference fossil system.

The most straight forward relation is with the fossil fuel used as a reference in the fossil scenario. Obviously, the more carbon intensive is the fossil fuel replaced, the shorter is the payback time. But this is a speculative assumption, as the fossil fuel replaced cannot be planned in advance; it is rather the result of market dynamics.

A further correlation exists with the efficiency of the biomass utilization. The less efficient is the bioenergy system the longer are the payback times. In case of electricity production, in biomass only plants, the electrical efficiency of biomass conversion is lower than the fossil, while thermal conversion energetic efficiency is similar for biomass and fossil fuels. In co-firing plants, biomass generally achieves the same efficiency as coal.

An intensive processing, such as for liquid biofuel substitution via lignocellulosic ethanol, causes much longer payback times because of the loss of energy in the biofuels production (about half of the energy content of the biomass is lost in the processing *[WTT 2011]*.

The payback time does not depend on the past of the forest but on the future growth rate of the forest. The slower is the forest growth rate the longer is the payback time. The forest growth rate depends on the latitude (boreal, temperate, tropical), but also on specific characteristics of the trees species, the microclimate and the soil fertility.

In all the results reported in Table 1 the production of biomass for bioenergy increases the productivity of the forest, therefore there is no displacement of wood for materials. Without an increase in productivity there would not be a payback time, as there would not be savings to pay back the forest carbon stock change.

Similar conclusions about the main factors influencing the payback times of bioenergy systems are reported also in Lamers et al. *[Lamers 2013a]*.

Table 1: Summary of the payback times calculated by the studies analyzed for bioenergy dedicated stemwood fellings in comparison to various reference systems

Source: own compilation by JRC

AUTHOR	AREA	FOREST TYPE	STUDY BOUNDARIES	SCENARIOS	FOSSIL SYSTEM	PAYBACK TIME (yr)
(McKechnie 2011)	Ontario	Temperate	Landscape	REF: BAU wood for products, BIO: BAU + additional harvest without residues	Electricity coal	38
					Gasoline (ethanol)	>100
(Holtsmark 2012a)	Norway	Boreal	Forest management unit	REF: BAU wood for products, BIO: BAU + additional harvest without residues	Electricity coal	190
					Gasoline (ethanol)	340
(Colnes 2012)	US SE forests	Temperate	Landscape	REF: BAU wood for products & energy , BIO: 22 new biomass power plants running on additional harvest in the same defined landscape	Various,	35 to 50
(Walker 2010)	Massachusetts	Temperate	Representative stand	REF: 2 baseline harvest scenarios (20-32%, no residues), BIO: 3 scenarios with additional harvest(38, 60, 76 % + 2/3 residues),	Oil, thermal or CHP	3-15
					Electricity coal	12-32
					Gas thermal	17-37
					Electricity Natural Gas	59 - >90
(Zanchi 2011)	Austria	Temperate	Forest Management Unit (90 ha)	Norway Spruce, Additional Fellings increased from 60% to 80% of Net annual increment (SFM), NO upstream emissions, only end use emissions (same for biomass and coal), 1) NO residues collection 2) residues collection only from the additional fellings	Electricity coal	1) 175 2) 75
(Zanchi 2011)	Austria	Temperate	Forest Management Unit (90 ha)	Norway Spruce, Additional Fellings increased from 60% to 80% of Net annual increment (SFM), NO upstream emissions, only end use emissions (N.G. 40% less emissions than biomass), 1) NO residues collection 2) residues collection only from the additional fellings	Electricity Natural Gas	1) 300 2) 200
(Zanchi 2011)	Austria	Temperate	Forest Management Unit (90 ha)	Norway Spruce, Additional Fellings (NO residues collection) increased from 60% to 80% of Aboveground biomass (no SFM), NO upstream emissions, only end use emissions 1) coal with same emissions as biomass	1) Electricity coal 2) Electricity Natural Gas	1) 230 2) 400 3) 295

AUTHOR	AREA	FOREST TYPE	STUDY BOUNDARIES	SCENARIOS	FOSSIL SYSTEM	PAYBACK TIME (yr)
				2) natural gas with 40% less emission than biomass 3) oil with 20% less emission than biomass,	3) Electricity Oil	
(Zanchi 2011)	Austria	Temperate forest	Forest management unit	Short rotation plantation on Marginal Agricultural Land with low C stock	Any fossil fuel	<0
(Zanchi 2011)	Austria	Temperate forest	Forest management unit	Forest Clearing – Substitution with short high productivity plantation (10 years rotation), wood for bioenergy. 1) coal with same emissions as biomass 2) natural gas with 40% less emission than biomass 3) oil with 20% less emission than biomass,	1) Electricity coal 2) Electricity Natural Gas 3) Electricity Oil	1) 17 2) 25 3) 20
(Zanchi 2011)	Austria	Temperate forest	Forest management unit	Forest Clearing – Substitution with short high productivity plantation (10 years rotation), 50% wood for bioenergy, 50% for HWPs (additional to baseline)	1) Electricity coal 2) Electricity Natural Gas	1) 0 2) 8
(Zanchi 2011)	Austria	Temperate forest	Forest management unit	Forest Clearing – Substitution with short low productivity plantation (20 years rotation), wood for bioenergy.	1) Electricity coal 2) Electricity Natural Gas 3) Electricity Oil	1) 114 2) 197 3) 145
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity,* biomass combustion efficiency 35% Reference: no harvest of plantation	Electricity from coal efficiency 41%	57/37/17
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 35% Reference: natural regrowth	Electricity from coal efficiency 41%	46/7/4
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 41% Reference: no harvest of plantation	Electricity from coal efficiency 41%	46/27/12
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 41% Reference: natural regrowth	Electricity from coal efficiency 41%	30/3/3
(Jonker	U.S.	Temperate	Forest	Softwood high productive plantation	Electricity from	39/21/8

AUTHOR	AREA	FOREST TYPE	STUDY BOUNDARIES	SCENARIOS	FOSSIL SYSTEM	PAYBACK TIME (yr)
2013)			Management Unit	Low/Medium/High management intensity, biomass combustion efficiency 46%** Reference: no harvest of plantation	coal efficiency 41%	
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 46% Reference: natural regrowth	Electricity from coal efficiency 41%	6/2/2
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 35% Reference: no harvest of plantation	Electricity Mix	106/68/39
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 35% Reference: natural regrowth	Electricity Mix	91/59/15
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 41% Reference: natural regrowth	Electricity Mix	72/41/9
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 41% Reference: no harvest of plantation	Electricity mix	80/55/28
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 46% Reference: no harvest of plantation	Electricity mix	69/46/21
(Jonker 2013)	U.S.	Temperate	Forest Management Unit	Softwood high productive plantation Low/Medium/High management intensity, biomass combustion efficiency 46% Reference: natural regrowth	Electricity Mix	60/25/6

**To be noted that the medium and high management intensity include fertilization among the practices. Currently only 4 % of the forests in the same area are fertilised [Fox 2006]. This percentage might, however, increase in the future.*

***The 46% efficiency for biomass combustion is not currently feasible, it may be a viable technology for a post 2020 scenario*

An additional factor that influences the payback time is the initial status of the land used for bioenergy production. This is analyzed by Mitchell et al. *[Mitchell 2012]*.

They consider four landscape conditions and land-use histories: afforesting post-agricultural land (age = 0), forest recovering from a severe disturbance (age = 0), old-growth forest (age > 200 years), and a forest harvested on a 50-year rotation (mean age ~25 years).

Furthermore, they distinguish between the fossil fuel parity point (the payback time used so far) and the carbon sequestration parity point (the time needed to recover the forest carbon stock loss and missed growth relative to an unmanaged forest scenario, via fossil fuel substitution) (see **Error! Reference source not found.**).

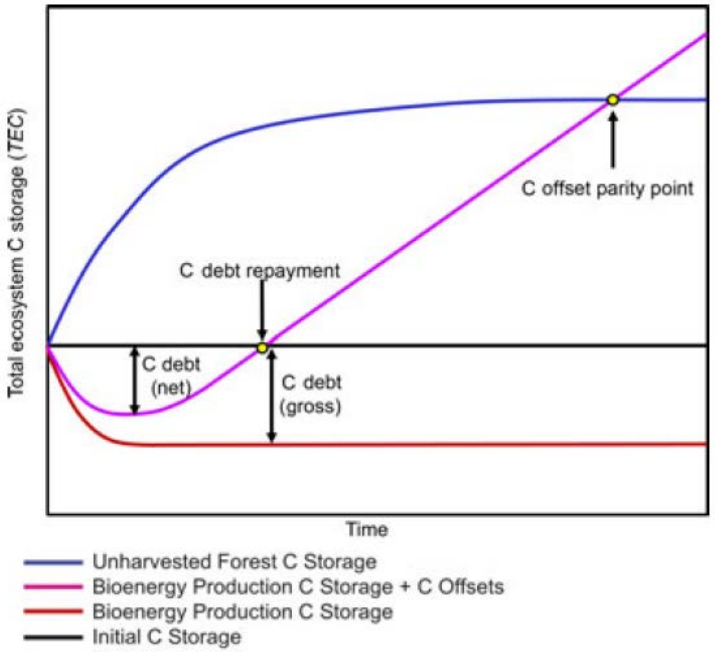

Figure 13: Conceptual representation of C Debt Repayment (fossil fuel parity) vs. the C Sequestration Parity Point. C Debt (Gross) is the difference between the initial C Storage and the C storage of a stand (or landscape) managed for bioenergy production. C Debt (Net) is C Debt (Gross) + C substitutions resulting from bioenergy production. Source: *[Mitchell 2012].*

The results of their analysis and a description of the scenarios run are illustrated in **Error! Reference source not found.** and **Error! Reference source not found.**.

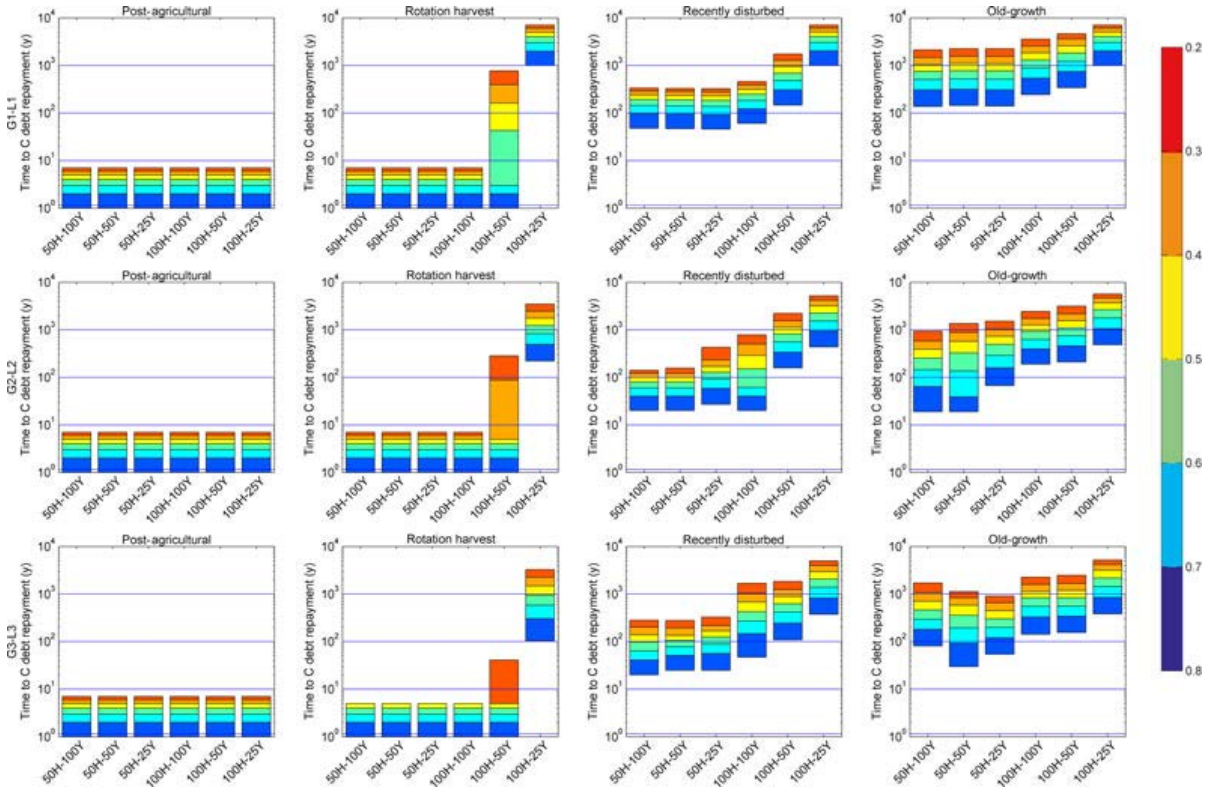

Figure 14: Comparisons of the time required for a repayment of the Carbon Debt among three ecosystem types , each with six biomass harvesting regimes and four land-use histories. The four land use histories are: Post-agricultural (age = 0), Recently disturbed (age = 0, disturbance residual carbon), Rotation forest (average age = 25, rotation=50), Old-growth (age > 200). Different harvesting regimes are indicated on the x-axis, with 50% and 100% harvesting intensity represented as 50H and 100H, respectively. Harvest frequencies of 25, 50, and 100 years are represented as 25Y, 50Y, and 100Y. Three combinations of biomass growth and longevity; G1, G2, and G3 represent increasing growth rates. L1, L2, and L3 represent increasing biomass longevities. The color scale represents the conversion efficiencies, ranging from 0.2 to 0.8, to ascertain the sensitivity of C offsetting schemes to the range in variability in the energy conversion process. Source: *[Mitchell 2012]*.

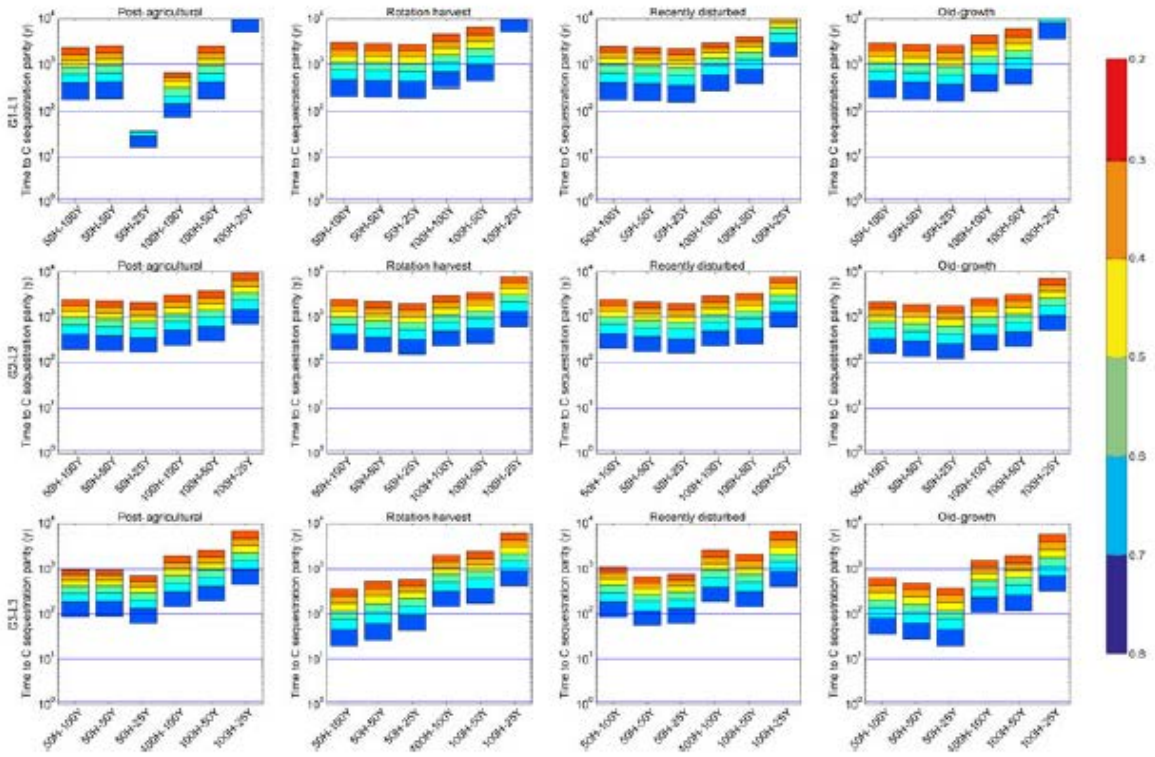

Figure 15: Comparisons of the time required to reach the Carbon sequestration parity among three ecosystem types, each with six biomass harvesting regimes and four land-use histories. The four land use histories are: Post-agricultural (age = 0), Recently disturbed (age = 0, disturbance residual carbon), Rotation forest (average age = 25, rotation=50), Old-growth (age > 200). Different harvesting regimes are indicated on the x-axis, with 50% and 100% harvesting intensity represented as 50H and 100H, respectively. Harvest frequencies of 25, 50, and 100 years are represented as 25Y, 50Y, and 100Y. Three combinations of biomass growth and longevity; G1, G2, and G3 represent increasing growth rates. L1, L2, and L3 represent increasing biomass longevities. The color scale represents the conversion efficiencies, ranging from 0.2 to 0.8, to ascertain the sensitivity of C offsetting schemes to the range in variability in the energy conversion process. Source: *[Mitchell 2012]*.

This analysis includes the simulation of wildfire occurrence with specific Mean Fire Return Intervals (MFRI) from literature.

The study concludes that the time required to reach the fossil fuel parity is usually much shorter than the time required for bioenergy production to reach the Carbon Sequestration Parity (see Figure 13). They confirm also that the effectiveness of substituting woody bioenergy for fossil fuels is highly dependent on the factors that determine bioenergy conversion efficiency, such as the C emissions released during the harvest, transport, and burning of woody biomass.

The frequency and intensity of biomass harvests should also be kept in high consideration; performing total harvests (clear-cutting) at high frequency may produce more bioenergy than less intensive harvesting regimes but may decrease C storage and thereby prolong the time required to achieve C Sequestration Parity.

The initial landscape conditions and land-use history are also fundamental in determining the amount of time required for forests to recover the initial additional emissions of the bioenergy system over the fossil one. While Recently Disturbed and Old-Growth landscapes required very long payback times, Post- Agricultural and Rotation Harvest landscapes were capable of recovering the additional emission in relatively short time periods, often within 1 year *[Mitchell 2012]*. This is a conclusion also of Zanchi et al. *[Zanchi 2011]*.

The reason is that planting a short-rotation forest on unused agricultural land does not start with high carbon stocks so causes an increase in average carbon stocks.

In **Error! Reference source not found.** are summarized the effects of the main factors on the payback time of stemwood bioenergy.

Table 2: Impact of various factors on payback times of stemwood bioenergy .

FACTOR	PAYBACK TIME
Higher Carbon intensity of substituted fossil fuel	Shorter
Higher Growth rate of the forest	Shorter
Higher Biomass conversion efficiency	Shorter
Higher Initial carbon stock	Longer
Higher Harvest level	Longer

2.1.2. Forest Residual wood

In this section the carbon balances of residual wood such as harvest residues and thinnings is analysed. These feedstocks are defined as residual material because the main aim of the forest management remains the production of wood for materials, they would be produced anyway and either left in the forest to decay or combusted at roadside (in the case of thinnings, competition with other uses is also possible, depending on the quality of the wood).

Harvest residues, when burned, will indeed release the same amount of CO_2 that had been previously stored from the atmosphere, however, they will release it all and at once, in a pulse. If the residues had been left in the forest, on the forest ground, the microbial or fungal decomposition and consequent CO_2 release would have still taken place but not to total conversion of the biomass into emissions and in a matter of years or decades, depending on the local climate conditions, the size of the harvested residues and the intensity of residues removal *[Repo 2012; Zanchi 2010]*.

The studies reviewed demonstrate that, concerning only the carbon stored in the harvested residues, after 20 years about half of the residues would still remain not decomposed, therefore burning them would actually mean reducing a carbon pool *[Zanchi 2010]*. In a policy timeframe of 20 years, the actual GHG emissions of the system should take this effect into account.

As already mentioned, one of the most important factors is the residue's size. **Error! Reference source not found.** shows the results of a study by Repo et al. *[Repo 2012]* in the case of energy generated from Norway spruce stumps (diameter 30 cm), young stand delimbed thinning wood (diameter 10 cm) and branches (diameter 2 cm) over a 100 years period after the start of the practice in Northern Finland (dotted line – lower temperature and precipitation) and Southern Finland (solid line – higher temperature and precipitation). To be noted that the emissions in **Error! Reference source not found.** refer to a MJ of fuel (wood, coal etc.). When the final conversion is included, the emissions from the biomass system equal, or can even be higher, than the emissions from coal in case of lower conversion efficiency (especially for lignocellulosic biofuels). Thus, the initial additional emissions of the bioenergy system are present even when considering substitution of coal. Moreover this study is at stand level, considering the landscape and the continuous harvest, the payback time would increase (as explained in the case of stemwood).

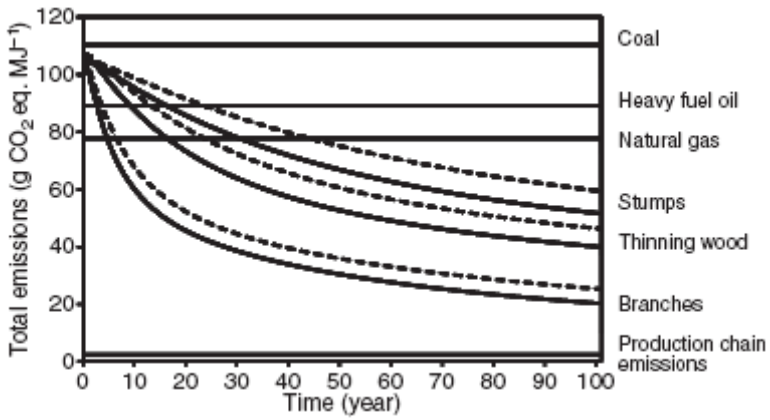

Figure 16: Total GHG emission per energy content from the production of energy from harvest residues. Norway spruce stumps (diameter 30 cm), young stand delimbed thinning wood (diameter 10 cm) and branches (diameter 2 cm). Emissions over a 100 year period after start of the practice in Northern Finland (dotted line) and Southern Finland (solid line) and the entire fuel cycle emissions of some fossil fuels. The total emission estimates of forest bioenergy include emissions resulting from the changes in carbon stocks and the emissions from production chain including collecting, transporting, chipping and combusting the forest residues. Source: *[Repo 2012]*.

Sathre and Gustavsson *[Sathre 2011]* analyzed, using cumulative radiative forcing (CRF) as indicator, the climate impact of bioenergy from forest residues (slash and stumps). Over a 240-year period, they found that CRF is significantly reduced when forest residues are used instead of fossil fuels. They found that the type of fossil fuel replaced plays an essential role. Coal replacement gives an almost immediate CRF reduction, but replacing oil and natural gas, despite resulting in long-term CRF reduction, causes an increment in the CRF during the first 10-25 years.

Error! Reference source not found. reports the results of the studies that have calculated the fossil fuel parity time of harvesting forest residues for bioenergy purposes.

The studies analyzed report payback times in the range of 0 – 74 years for harvest residues. The main factors affecting these values are mostly similar to the ones described for stemwood. The ratio of fossil carbon displacement is the main parameter. If the residues are used with high efficiency to displace coal (such as in co-firing), the payback times are rather short, if any. In case the residues are heavily processed to produce liquid biofuel the payback time increases dramatically. Also the size of the residue plays a relevant role, as well as the geographic and local conditions that influence the bacterial decomposition rates.

Wood from thinnings may, to some extent, be assimilated to harvest residues (especially pre-commercial thinnings). If not collected for bioenergy it would be left in the forest to decay, or combusted at roadside. On the other hand, depending on the wood quality, the use of thinnings wood for bioenergy may compete with other uses, such as pulp and paper or engineered wood.

Salvage loggings can also be assimilated to harvest residues. Damaged, dying or dead trees affected by injurious agents, such as wind or ice storms or the spread of invasive epidemic forest pathogens, insects and diseases would remain in the forest and decay or combusted at roadside. Wood removed for prescribed fire hazard control as well can be considered residual wood.

Table 3: Summary of the payback times calculated by the studies analyzed for harvest residues in comparison to various reference systems

Source: own compilation by JRC

AUTHOR	AREA	FOREST TYPE	STUDY BOUNDARIES	SCENARIOS	FOSSIL REFERENCE SYSTEM	PAYBACK TIME (yr)
(McKechnie 2011)	Ontario	Temperate	Landscape	REF: BAU wood for products, RESIDUES = BAU + residues harvest,	Electricity coal	Residues 16
					Gasoline (ethanol)	Residues 74
(Zanchi 2011)	Austria	Temperate	Forest Management Unit	Norway Spruce, Fellings Residues (from baseline felling rates and no leaves) increased from 0% to 14% of aboveground biomass left from fellings, NO upstream emissions, only end use emissions 1) coal with same emissions as biomass 2) natural gas with 40% less emission than biomass 3) oil with 20% less emission than biomass,	1) Electricity coal 2) Electricity Natural Gas 3) Electricity Oil	1) 0 2) 16 3) 7
(Repo 2012)	Finland	Boreal	Forest stand	Baseline scenario clear cut for materials; 3 scenarios with different residues harvest	Electricity Natural gas	Branches 8 Thinning 20 Stumps 35
(Repo 2012)	Finland	Boreal	Forest stand	Baseline scenario clear cut for materials; 3 scenarios with different residues harvest	Electricity Heavy fuel oil	Branches 5 Thinning 12 Stumps 22
(Mitchell 2009)	U.S.	Temperate	Forest stand	Coast range forest type Forest biomass removed for fire prevention Understory removal, overstory thinning, and prescribed fire every 25 years	Average fossil fuel via solid biomass	old growth 169 second growth 34
(Mitchell 2009)	U.S.	Temperate	Forest stand	Coast range forest type Forest biomass removed for fire prevention Understory removal, overstory thinning, and prescribed fire every 25 years	Average fossil fuel via ethanol	old growth 339 second growth 201

AUTHOR	AREA	FOREST TYPE	STUDY BOUNDARIES	SCENARIOS	FOSSIL REFERENCE SYSTEM	PAYBACK TIME (yr)
(Mitchell 2009)	U.S.	Temperate	Forest stand	West cascades forest type Forest biomass removed for fire prevention Understory removal, overstory thinning, and prescribed fire every 25 years	Average fossil fuel via solid biomass	old growth 228 second growth 107
(Mitchell 2009)	U.S.	Temperate	Forest stand	West cascades forest type Forest biomass removed for fire prevention Understory removal, overstory thinning, and prescribed fire every 25 years	Average fossil fuel via ethanol	old growth 459 second growth 338

2.2. Correction factors for attributional LCA and other indicators for energy systems comparison

This approach is what we will call Biogenic Emission Factor approach. In this case all the parameters influencing the biogenic carbon accounting of biomass (both for residues and for stemwood) are combined into a single emission factor that is added to the LCA results achieved with the biomass carbon neutrality assumption (e.g. RED Annex V).

2.2.1. GWP_{bio}

The GWP_{bio} has been introduced by Cherubini et al. *[Cherubini 2011a; Cherubini 2011b]* who have assumed that biogenic-CO_2 released from biomass combustion should be treated as any other GHG and thus assigned a proper Global Warming Potential (GWP_{bio}) expressed as a function of the rotation period of the biomass.

The GWP is a measure of the effect of the pulse emission of a unit (mass) of a certain gas over its lifetime on the radiative properties of the atmosphere for a certain period of time. In the methodology designed by the IPCC *[IPCC 2006]*, the GWP of CO_2 is taken as the reference value and assigned the value of 1. The reasoning of the authors is that biogenic CO_2 has indeed the same radiative effect of fossil CO_2 on the atmosphere but, while fossil CO_2 can only be reabsorbed by oceans and biosphere (according to the formulation using Bern CC equation, as given by *[IPCC 2006]*), biogenic-CO_2 has an additional factor which is the re-absorption of the CO2 via re-growth of vegetation on the same piece of land. By this mathematical formulation, they have been able to assign various values of a so-called GWP_{bio} over the typical time horizons of 20, 100 and 500 years and depending on the timing of biomass re-growth. Technically, this factor can then be simply used in a classical LCA and applied as correction factor to the amount of the biogenic-CO_2 emitted by the combustion of biomass.

Table 4: GWP_{bio} index calculated for three different time horizons. Example with the Full Impulse Response Function (FIRF). Source: *[Cherubini 2011a]*.

Rotation (years)	Full Impulse Response Function (FIRF)		
	GWP_{bio} TH = 20 years	GWP_{bio} TH = 100 years	GWP_{bio} TH = 500 years
1	0.02	0.00	0.00
10	0.22	0.04	0.01
20	0.47	0.08	0.02
30	0.68	0.12	0.02
40	0.80	0.16	0.03
50	0.87	0.21	0.04
60	0.90	0.25	0.05
70	0.93	0.30	0.05
80	0.94	0.36	0.06
90	0.95	0.39	0.07
100	0.96	0.43	0.08

A sample of the values found by Cherubini et al. *[Cherubini 2011a]* for the GWP_{bio} is given in **Error! Reference source not found.** as a function of the time horizon chosen and the length of the rotation (annual crops have an rotation of 1 year, wood from boreal forests

have a rotation of about 80-100 years).

This approach has the advantage of fitting easily within current LCA practices and it offers a simple, general solution that can be easily parameterized according to the specificities of the various systems with an acceptable accuracy.

However, the GWP_{bio} as reported in **Error! Reference source not found.**, is not a feature of the system that has produced the bioenergy, but rather of the bioenergy system that will follow it. It is based on the assumption that the bioenergy system will not change in the next production period. Moreover the use of such a parameter may result counterproductive as it may lead to shortening the rotation periods to get a lower GWP_{bio} that, unless the management and species are changed, would lead to a lower productivity and lower forest carbon stock, with a permanent atmospheric CO_2 increase as the lower productivity would not allow for the payment of the carbon stock change in the forest.

2.2.2. Carbon neutrality factor

The second methodology has been introduced by Schlamadinger et al. *[Schlamadinger 1995]* and applied in modified form more recently by Zanchi et al. *[Zanchi 2010]*. They have introduced a so-called carbon neutrality factor (CN) which basically relates the cumulative CO_2 emissions of the reference fossil system with the ones due to the bioenergy system (CO_2 emissions due to the carbon stock change in the forest) at different time horizons. The CN has been recently used also by other authors *[Pyörälä 2012]*.

When this value is lower than 0, the bioenergy system has emitted more than the fossil system. A CN=0 represents the fossil fuel parity. When CN is higher than 0 the system is saving GHG compared to the fossil fuel system. When CN is equal to 1 it means that the atmospheric carbon parity has been reached. In case the CN > 1, the bioenergy system, beside replacing the fossil system, is reducing atmospheric CO_2 (via CO_2 absorption because of positive dLUC or offsetting fossil emissions)

This method is able to mimic properly the dynamic nature of the biogenic carbon emissions and it basically condenses the results from a forest model into a single value. However, the carbon neutrality factors are only defined based on specific growth rates and for specific fossil fuels reference systems (a techno-economic model should be used to identify the most likely displaced energy source).

Some examples of CN values are given in **Error! Reference source not found.** as a function of different time horizons and different reference systems.

Table 5: Examples of Carbon Neutrality Factors as calculated by Zanchi et al. *[Zanchi 2010]*.

Carbon Neutrality Factors				
Source of biomass	20 years	50 years	300 years	Notes
Forest residues (constant annual extraction)	0.6	0.7	0.9	Always positive but not C neutral
Additional thinnings	< 0	< 0	0.2	Atmospheric benefit after 200 -300 years
New forests from conversion from cropland	≥ 1	≥ 1	≥ 1	C neutral
New forests from conversion from grassland	> 0 to ≤ 1	≥ 1	≥ 1	Positive in the short-term, becomes C neutral in 1 – 2 decades
Conversion from managed forest to SRC	< 0	< 0	0.7	Atmospheric benefit after 70 years
Conversion from mature forest to SRC	< 0	< 0	0.4	Atmospheric benefit after 170 years
Conversion from managed forest to a 60 year rotation plantation	< 0	< 0	0.3 – 0.7	Atmospheric benefit after 150 – 200 years

2.3. Soil organic carbon

Several studies have suggested that harvested residue removal or forest floor disturbance could have implications for the long-term storage of soil carbon and nitrogen with possible impacts on forest productivity *[Berndes 2012; Chen 2005; Cowie 2006; Helmisaari 2011;l Jones 2011; Jones 2008; Laiho 2003; Powers 2005; Smaill 2008; Thiffault 2011]*.

Johnson, and Curtis *[Johnson 2001]* carried out a meta-analysis of the literature covering effects of forest management on soil carbon and nitrogen storage and concluded that forest harvesting, despite a very high uncertainty, on average, had no overall effect on carbon storage in soils.

However, significant effects of harvest type and species were noted, with saw log harvesting causing increases (+18%) in soil C and N and whole tree harvesting causing decreases (-6%). The positive effect of saw log harvesting appeared to be restricted to coniferous species.

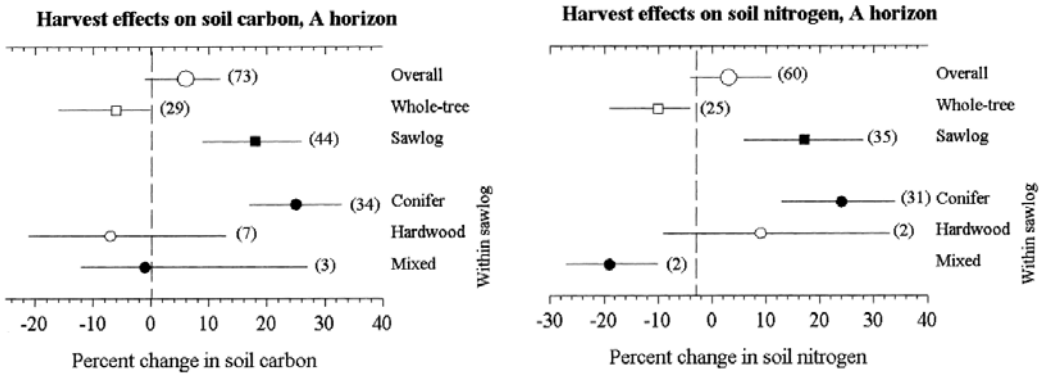

Figure 17: Plot of A horizon non-parametric meta-analysis results for soil C and N with harvesting. 99% confidence intervals and number of studies (in parenthesis) are shown. Source: *[Johnson 2001]*.

Nave et al. *[Nave 2010]* in their review of 75 publications between 1979 and 2008 found that forest harvesting (encompassing intensities and residue management practices) resulted in a significant 8% decrease in total soil-C on average in temperate forest soils (**Error! Reference source not found.**).

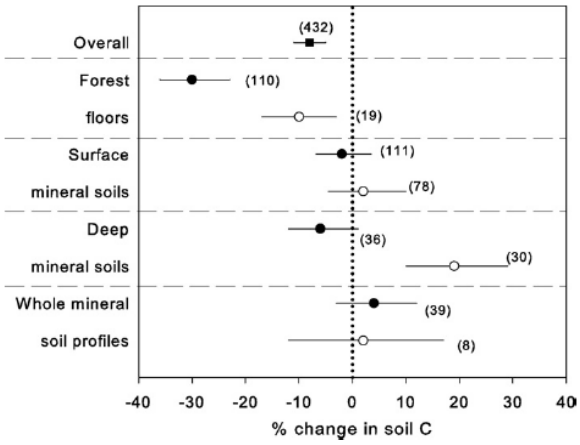

Figure 18: Soil C changes due to forest harvesting, overall and by soil layer. All points are mean effect sizes with the number of studied in parenthesis. Source: *[Nave 2010]*.

Concerning the soil carbon and nutrients stocks, Repo et al. *[Repo 2011]* showed that the extraction of residues beyond a certain amount would result in the alteration of the soil fertility and affect the overall forest carbon balance negatively.

Jones et al. *[Jones 2011]* demonstrated that carbon and nitrogen storage in the forest floor would be reduced through to mid-rotation and possibly beyond, by harvest residue removal, independently of the intensity of the removal management. Furthermore, harvest residue manipulation may have implications for the productivity of the replanted trees. Full recovery of the forest floor pool in C and N stocks following complete forest floor removal would have occurred in about 20 years. This time for total recovery can vary depending on the climate and microclimate, the mineral soil texture and the organic content in carbon, nitrogen, phosphorus and other nutrients and the characteristics of regenerating species.

A recent paper by Schulze et al. *[Schulze 2012]* argues whether removal of harvest residues will reduce soil fertility, making the bioenergy production unsustainable unless enhanced through fertilization, (which in turn would increase GHG emissions due to fertilizers production and application emissions). Similar arguments are presented by Berndes et al. *[Berndes 2012]*, but C stock losses are small compared with the increase in accumulated harvest in the longer term. Fertilizer inputs can compensate for nutrient removals connected to harvest and residue extraction, but maintenance or improvement of soil fertility, structural stability and water-holding capacity requires recirculation of organic matter to the soil. As a result, the site-specific constraints should be taken into consideration.

Another recent study reports a decrease in the amounts of exchangeable base cations (Ca, K and Mg) after whole-tree thinning, but not significant changes in the amounts of nitrogen in the soil, results that were expected since K and Mg in logging residues corresponds on average to 60-70 % and 30-40 % respectively of the total amounts of nutrients in the organic layer *[Tamminen 2012]*. On the contrary nitrogen corresponds only to 10%.

The effect of harvest and replanting on soil carbon is difficult to generalize, as much depends on the initial soil depth, the depth to which soil is sampled, and postharvest site preparation. The measured effects tend to be slight in the short term, with carbon decreases concentrated in the forest floor and near the soil surface and carbon increases occurring in the deep mineral soil layers. Whole-tree harvesting for biomass production has little long-term effect on soil carbon stocks if surface soil layers containing organic material (O horizon) are left on site, nutrients are managed, and the site is allowed to regenerate *[Malmsheimer 2011]*.

2.4. Analysis of system boundaries, reference system and timeframe choice

The previous sections have shown how the large range of forest types and forest management choices, as well as the large number of bioenergy and biofuel pathways and the variety of alternative energy systems they may replace lead to a very high variability of GHG performances in terms of bioenergy GHG emission reductions when compared to fossil fuels.

The main reasons for diverging results are: type of biomass sources, assumptions about the alternative land use and its impacts, conversion technologies, input data sources, end-use technologies, allocation method, system boundaries, reference energy system and other assumptions (such as land-use change effects, soil N_2O emissions, data quality and age, etc.) *[Cherubini 2009; Cherubini 2010]*.

The influence of some of the listed parameters is quite obvious, while the impact of the definition of the system boundaries and the reference system have often been underestimated.

As explained in section **Error! Reference source not found.**, the carbon stock changes in the forest resulting from the use of the biomass for bioenergy need to be accounted for, but the reference system (fossil fuels use) should also include what would happen to the forest carbon stock in the absence of bioenergy production *[Mitchell 2012]*.

Johnson and Tschudi *[Johnson 2012]* have identified four different types of baselines. In 'no baseline' all the biomass is considered carbon neutral. In 'reference point' only the changes from the initial carbon stock in the forest are accounted for. In 'marginal fossil fuel' the carbon footprint of bioenergy equals net carbon emissions from a forest (as for the reference point) minus avoided emissions from a fossil-fuel-fired alternative. With what they call 'biomass-opportunity-cost' baseline, the bioenergy emissions equal the carbon stock changes in the forest, minus the avoided fossil emissions plus the lost future sequestration. They conclude that the choice of the baseline has the greatest single influence on bioenergy carbon footprint.

Table 6: Wood-fired electricity footprints , by baseline type, 100 y time horizon. a) The marginal average fossil fuel, in both cases, is a UCTE average for power plants using these fuels, as reported in Ecoinvent Version 2.1. UCTE is an interconnected power grid that covers most of continental Western Europe. The 'natural gas, state-of-the-art' uses the footprint of, at the time of this writing, the world's most efficient combined-cycle power plant, operated by E.ON in Irsching, Germany. Source: *[Johnson 2012]*.

Baseline	Absolute footprint (g CO_2 / kWh)	Relative footprint (as a multiple of 'no baseline')
No baseline	39	1.0
Reference point	266	6.9
Marginal fossil fuel:		
Natural gas, average	-107	-2.8
Natural gas, state-of-the-art	135	3.5
Coal, average	-544	-14.0
Biomass opportunity cost	536	13.9

In the US, the EPA *[EPA 2011]* had included biogenic CO_2 emissions from stationary sources in the Clean Air Act permitting requirements. In response to a petition from forest owners, in July 2011 the permitting requirements for biogenic CO_2 were deferred for three

years. In the meanwhile a methodological framework for accounting for biogenic CO_2 emissions from stationary sources has been proposed and is under evaluation. In their framework they have initially suggested to use a 'reference point' baseline. However, this choice has recently been criticized by the EPA Scientific Advisory Board, that suggests a 'biomass-opportunity-cost' baseline *[EPA 2012]*.

In the framework of the U.N.F.C.C.C., the LULUCF accounting rules agreed in 2011 in Durban, beside making forest management accounting mandatory for the 2nd Kyoto Protocol commitment period, establishes that the accounting will be through the "reference level approach", i.e. projected reference forest sink up to 2020 (what has been defined in this report as 'biomass opportunity cost' *[UNFCCC 2011]*.

Obviously, in defining the system boundaries all the processes that are common to both the fossil and the bioenergy system should be left out of the analysis. It is not correct to allocate the carbon intake of a whole region/country to a specific bioenergy pathway, since the carbon intake of the region would be the same, and even higher, with the fossil system. Therefore, only the part of the forest that is (directly or indirectly) involved for the bioenergy production should be included in the carbon accounting.

In comparative LCA studies the choice of the reference system to which the bioenergy emissions are compared is fundamental. The first important choice is between the marginal reference system and the current average per MJ (heat, electricity or fuel). In case the marginal reference is chosen, then assumptions have to be made on which technology is replaced and whether the competing technology is based on fossil or renewable sources and how it will change in time.

The timeframe of the comparison too plays a relevant role in the performances of the reference system. If the timeframe chosen is short, the current emissions from the reference system can be considered appropriate and constant. In the case of a long-term analysis, though, also the changes in the fossil reference system have to be accounted for. For instance, practically in all of the studies analyzed the reference system (coal or NG) is kept constant and unchanged for the whole duration of the analysis (even centuries), while, according to EU policies, by 2050 the EU should be decarbonized, implying that future savings might be much smaller than current ones. In this case, as reported in **Error! Reference source not found.**, it may happen that the payback time is never reached.

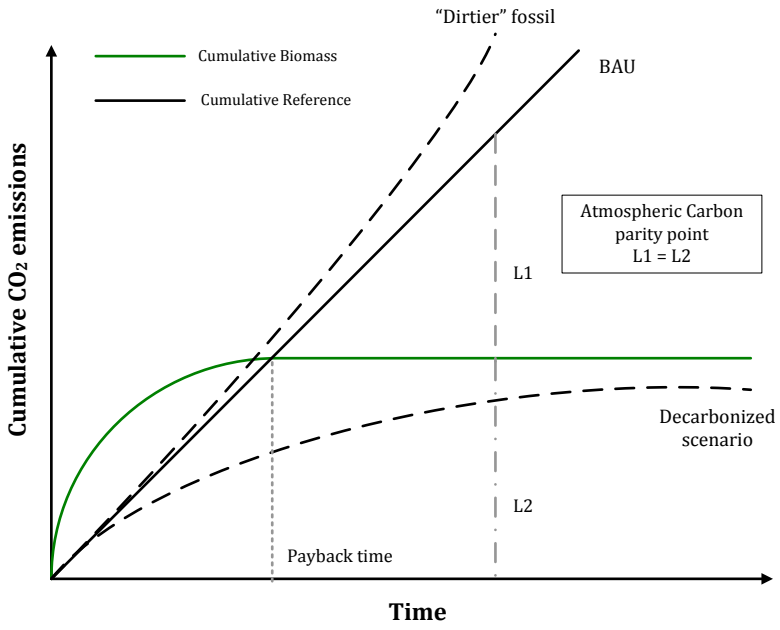

Figure 19: Visual description of payback time and atmospheric carbon parity with a dirtier or cleaner reference system.

On the other hand, if the reference fossil system gets 'dirtier', as in the case of most of the unconventional fossil energy (shale gas, bituminous coal etc.) the fossil fuel parity may be reached sooner than with a constant reference fossil fuel. A further risk is that the land available for biomass harvest today may not be available to the energy sector long enough (sometimes century timescale) for the initial emissions to be compensated.

Which fossil source of energy is actually displaced depends on the specific situation of the energy markets in which the renewable energies are introduced. Currently, because of the peculiarity of the European energy market, according to an article published in The Economist *[The Economist 2013]*, renewable energies in Europe are replacing natural gas, as a whole.

2.5. Relevance of forest bioenergy carbon accounting for future bioenergy pathways

It is important to underline that the inclusion of the dynamic carbon balances in forest bioenergy LCA does not change the GHG mitigation potential of waste wood and industrial wood residues, the most common feedstocks for pellets production as of today. On the other hand it is worth noting that, according to the NREAPs the amount of bioenergy from such residues (called indirect wood) is expected to be stable (or even to decrease slightly) while the wood sourced directly from the forest (from additional fellings, harvest residues, complementary fellings, salvage loggings, etc.) is expected to increase by 50% between 2006 and 2020 (Table 7).

Table 7: Biomass domestic supply in the EU [PJ]. ***[Scarlat 2013]***

	2006	**2015**	**2020**
Direct wood	1264	1545	1807
Indirect wood	1382	1260	1329

According to Lamers et al. *[Lamers 2012],* in recent years, declines in sawmill output have caused stemwood from bioenergy dedicated harvest to be used as input material in pellet production. This is also partly related to trends in paper production, i.e. a shift in production from the Northern to the Southern hemisphere; leaving Scandinavia, North America, and Russia with considerable surpluses of wood and causing whole stems to be used for bioenergy. Furthermore, the authors state that in the future, expected regional shortages of industrial roundwood supply, the expansion of biorefinery concepts, and liquid biofuel production from lignocellulose might also affect energy-related roundwood trade.

This phenomenon is reported also in a study by IEA Bioenergy task 40 "Global wood Pellet Industry Market and Trade Study" *[Cocchi 2011]*. The report shows that the pellets production from stemwood bioenergy dedicated harvest is projected to increase in the future (**Error! Reference source not found.**).

Furthermore the IEA Bioenergy Task 40 study *[Cocchi 2011]* reports that the new large pellets plants (such as Greencircle, Florida, 500 ktonnes; Waycross, Georgia, 750 ktonnes; Vyborgskaya, Russia, 1000 ktonnes) will rely mostly on stemwood from dedicated bioenergy harvest as feedstock.

As regards woodchips used for bioenergy, a recent literature review and survey from Díaz-Yáñez et al. *[Díaz-Yáñez et al, 2013]* reports that industrial roundwood from final felling contributes with a share of about 10 % to the total amount of estimated current use of

woodchips for bioenergy (**Error! Reference source not found.**). The same share is expected for the potential use of stemwood dedicated harvest for chips to be used for bioenergy. In this study too is expected a shift towards increasing the utilization of whole trees, roundwood from final fellings and stumps for bioenergy purposes.

From these estimates and projections it can be concluded that the issues related to forest bioenergy carbon will be more relevant in the future bioenergy pathways.

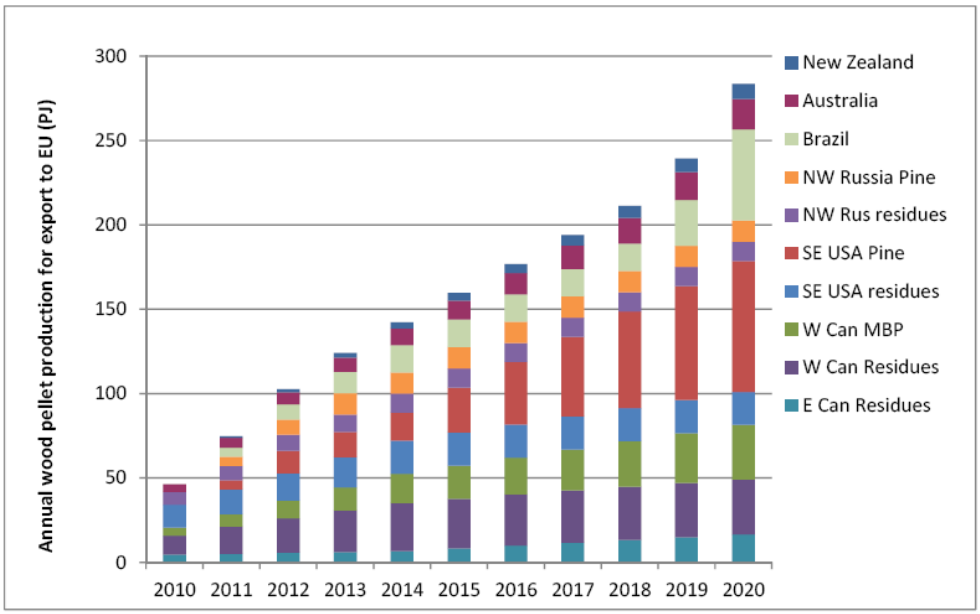

Figure 20: Anticipated growth in available solid biomass supply from the various sourcing regions. Residues = woody industry residues (e.g. sawdust), MPB = Mountain pine beetle affected wood. ***[Cocchi 2011]***

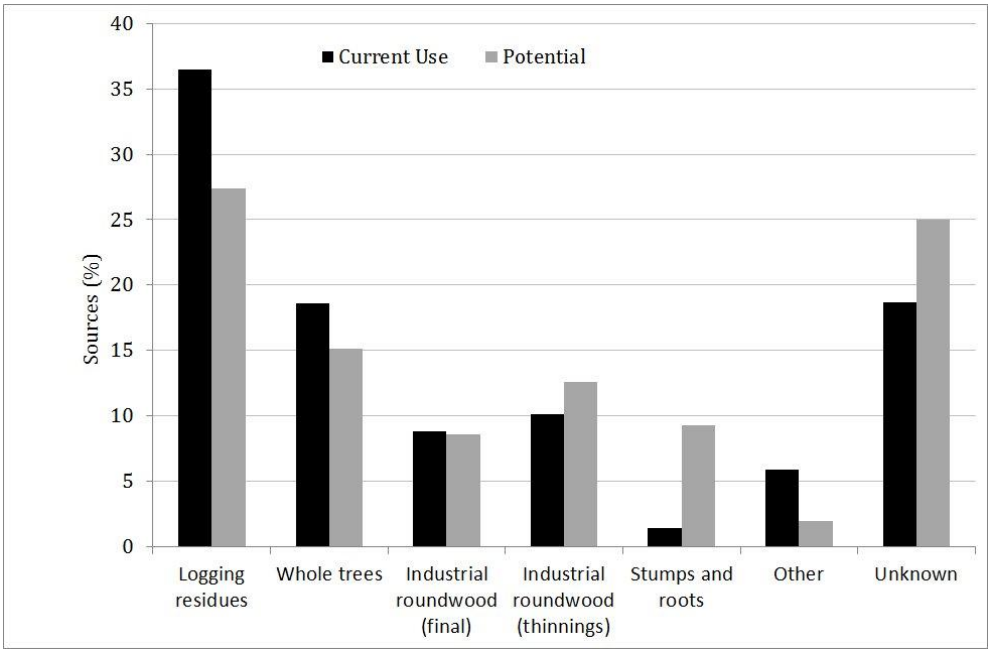

Figure 21: Comparison of the sources of raw material of wood chips for energy for estimated current use and potential. ***[Díaz-Yáñez, 2013]***

3. Other climate forcers

In assessing the Global Warming impact of bioenergy often only the Long Lived GHG (CO_2, CH_4, N_2O and halocarbons) are considered (if not just CO_2), but the energy balance of the earth climate system is altered also by changes in the atmospheric concentration of other gases and aerosols (directly emitted or precursors), in solar radiation and in land surface albedo.

The influence of these climate forcers on global climate is expressed in terms of radiative forcing. Figure 22illustrates the difference in radiative forcing of the main climate forcers from the pre-industrial age, while Figure 23illustrates the radiative forcing of principal gases, aerosols and aerosol precursors.

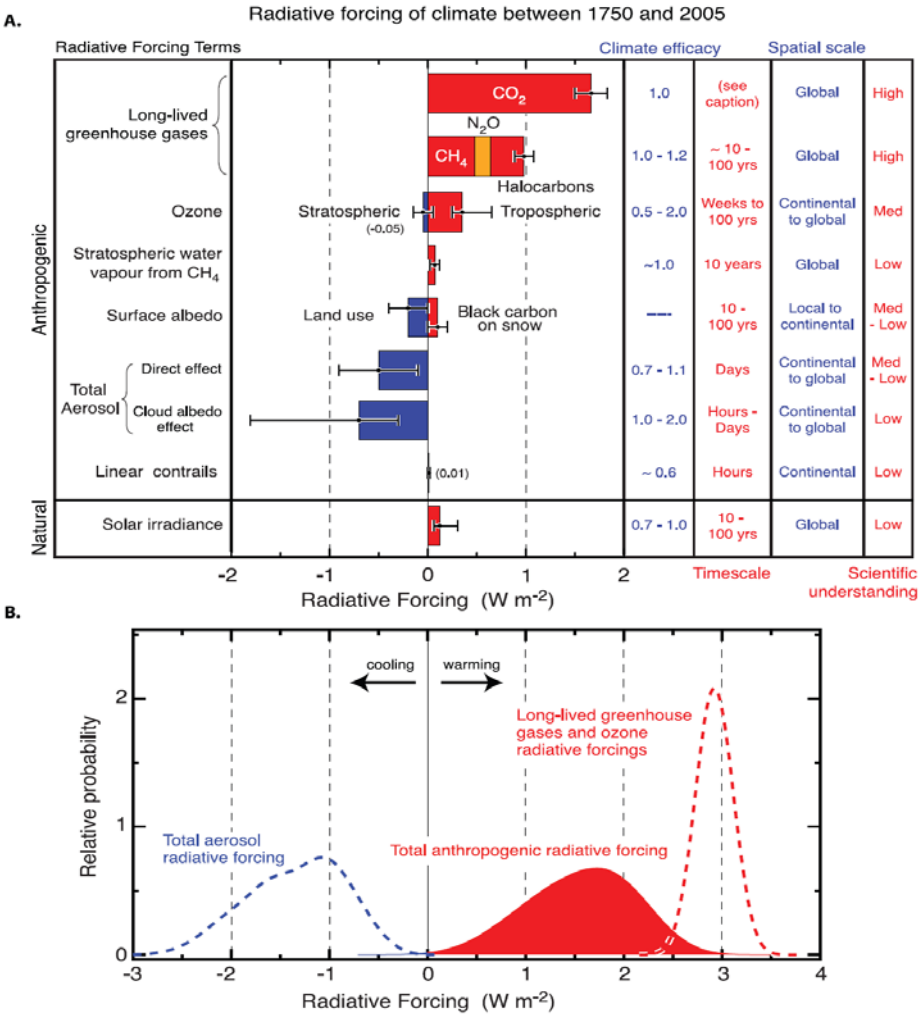

Figure 22: Radiative forcing of climate between 1750 and 2005. (A). Global mean RFs grouped by agent type. Columns indicate other characteristics of the RF; Time scales represent the length of time that a given RF term would persist in the atmosphere after the associated emissions and changes ceased. No CO2 time scale is given, as its removal from the atmosphere involves a range of processes that can span long time scales, and thus cannot be expressed accurately with a narrow range of lifetime values. (B) Probability distribution functions (PDFs) from combining anthropogenic RFs in (A). Three cases are shown: the total of all anthropogenic RF terms (block filled red curve); LLGHGs and ozone RFs only (dashed red curve); and aerosol direct and cloud albedo RFs only (dashed blue curve). Surface albedo, contrails and stratospheric water vapour RFs are included in the total curve but not in the others. Source: *[IPCC 2007]* AR4-WGI-Ch2-pg203.

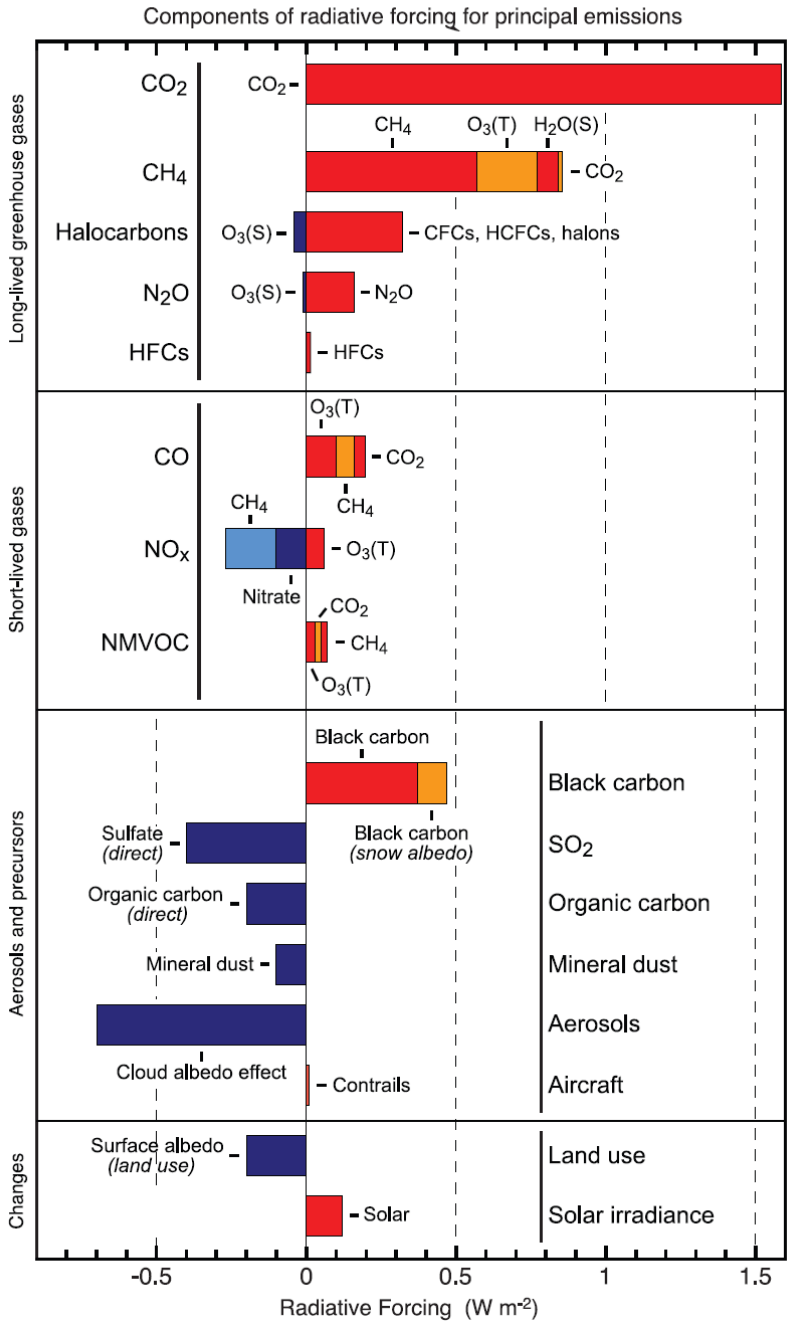

Figure 23: Components of radiative forcing for principal gases, aerosols and aerosol precursors and other changes. Values represent RF in 2005 due to emissions and changes since 1750. (S) and (T) next to gas species represent stratospheric and tropospheric changes, respectively. Source: *[IPCC 2007]*.

Bioenergy impacts the climate through all of the climate forcers except for the solar irradiance, thus a complete assessment of the climate impact of bioenergy should include all of the climate forcers. On the other hand, as the uncertainties are so large and tend to counterbalance each other, the analysis are limited to long lived GHG. Moreover, the efficacy of other forcers depends on the local conditions of the atmosphere and albedo.

There is substantial controversy about the applicability of GWP metrics to short-lived substances but, just as an example, in Table 8, the GWP100 chosen by UNEP are reported; in any case they would depend on the specific biomass used, the technology and the geographic area *[UNEP 2011]*.

Table 8: Contribution to long-term climate objective (GWP100) chosen as selection criterion for measures based on literature ranges of GWP100. Source: *[UNEP 2011]*.

	Mean value	Range
CO_2	1	
CH_4	25	16 – 34
CO	1.9	1 – 3
VOC	3.4	2 – 7
BC	680	210 – 1500
SO_2	-40	-24 - -56
OC	-69	-25 - -129
NO_x	~ 0	

Black carbon (BC) causes a positive radiative forcing through direct absorption of solar radiation, but it indirectly induces changes in cloud properties, and also changes snow albedo once it deposits on the surface. Black carbon radiative forcing due to absorption alone may be about half that of anthropogenic CO_2.

There is large uncertainty in determining the overall contribution of BC to radiative forcing. Black carbon, like other aerosol particles, interacts with clouds, changing their reflectivity and lifetime, with effects on local and global climate. In addition, when calculating the climate effect of BC, it is important to realize that it is often mixed with organic carbon (OC) which is also produced during combustion and which reflects sunlight much more strongly than it absorbs it. A low OC-to-BC ratio means a predominantly absorbing aerosol that will contribute to warming. A high OC-to-BC ratio means a predominantly reflecting (or scattering) aerosol that will contribute to cooling. The ratio depends on the emission source: it can be lower than 1 in the case of emissions from diesel engines, but will be much higher in the case of, for example, smoldering wood (Table 9).

Table 9: Emission factors for combustion of coal and biomass (mg/MJ). Source: [Kupiainen 2007].

Combustion Technique	Control Technology	Biomass		Brown coal		Hard coal	
		BC	OC	BC	OC	BC	OC
Fireplace	Uncontrolled	75 – 100	375 – 500	-	-	-	-
Stove	Old	75 – 105	225 – 315	24	312	130	200
	New	56 – 79	11 – 16	24	312	130	200
Boiler < 50 kWth (manual feed)	Old	75	113	29	300	215	175
	New	75	113	26	120	194	70
Boiler < 1 MWth (manual feed)	Uncontrolled	35	25	2.3	5.0	4.0	2.0
Boiler < 50 MWth (automatic feed)	Uncontrolled	7.5	8	2.3	5.0	4.0	2.0
Pellet boiler < 50 MWth (automatic feed)	Uncontrolled	0.83	0.83	-	-	-	-
Industrial grate firing	Uncontrolled	9.6	14	4.5	18	6.0	3.0

Black carbon impacts also surface albedo if deposited on snow and ice, but, being a short lived climate forcer, this impact is relevant only if emitted close to ice or snow covered surfaces (such as Himalaya or the Poles).

Sulphate emissions, that have a cooling effect on global climate, have been reduced in industrialized countries and will likely be further reduced over the coming decades due to a focus on problems related to human health, acid rain. According to Ramanathan sulphate emission reduction which will lead to accelerated warming *[Ramanathan 2008].*

Anthropogenic ozone global radiative forcing is about one-sixth to one-third that of CO_2. Ozone is not an emitted pollutant and thus for control purposes it is appropriate to attribute the radiative forcing for ozone to its precursors, such as methane, carbon monoxide,, non-methane volatile organic compounds (NMVOC) and nitrogen oxides. Two-thirds of the ozone radiative forcing to date may be attributed to the increase in atmospheric methane over the last century *[UNEP 2011]*.

The emissions of NO_X contribute a small fraction of the ozone radiative forcing, but other effects of NO_X emissions have a greater negative radiative forcing effect, in particular the atmospheric destruction of CH_4 and the direct and indirect aerosol effects. Thus the net radiative effect of NO_X is negative. NMVOC and CO emissions make small positive contributions to the radiative forcing through effects on ozone *[UNEP 2011]*.

Effects of albedo (changes in surface reflectivity), evaporation/transpiration, and surface roughness play a relevant role in the regulation of energy fluxes and the water cycle, affecting climate across various temporal and spatial scales *[Johnson 2009; Lim 1999]*.

Several experts suggest that current "carbon-only" approaches, which ignore the albedo effect, are “incomplete” as GHG units do not reflect the entire picture *[Schlamadinger 1996; Schlamadinger 2007; Schwaiger 2010; Anderson 2010; Robert 2008; Trømborg 2011]*.

In tropical regions, afforestation may be beneficial since beside sequestering carbon it can lead to cloud formation resulting in a net cooling. In boreal regions, however, low surface albedo of afforested areas might have a warming climatic forcing that "may exceed the cooling forcing from sequestration" *[Thompson 2009]*.

Bright et al. have defined a possible way of integrating the impact on albedo in the LCA of a forest biofuel *[Bright 2012]*. They have defined a GWP_{α} following the same approach as the GWP_{bio} (see Section **Error! Reference source not found.**). This characterization factor is region and case specific. In their paper an example for the clear-cut of a boreal forest is reported. In that specific case the increase in albedo that follows the clear-cut harvest may offset about half of the total CO_2 emissions (that include also the biogenic emissions due to carbon stock changes) in a 100 years timeframe.

Also Schwaiger and Bird *[Schwaiger 2010]* have attempted to integrate albedo effects into the bioenergy GHG calculations. They have considered an afforestation project in a south European mountainous area and used average yearly meteorological data. They have concluded that afforestation in the case study area accumulates up to 624 t $CO_{2\ eq.}$/ha, while the change in albedo due to crown cover is equivalent to emissions of roughly 401 t $CO_{2\ eq.}$/ ha by the end of the first rotation period (90 years). The net effect, thus, varies around a neutral level with the cumulative result of a slight cooling in the long term.

The trend in the long term is reported in **Error! Reference source not found.**.

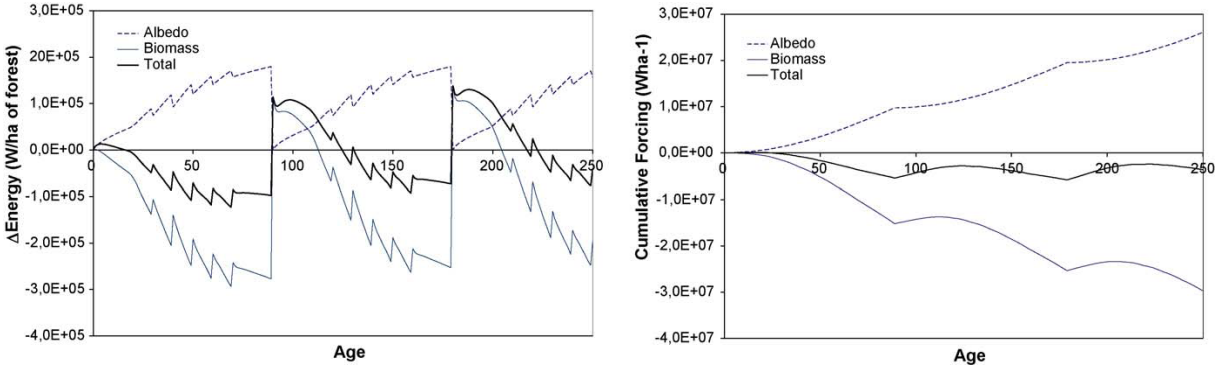

Figure 24: Biomass, albedo and total radiative forcing effects due to Scot pine forest.a) Annual impacts over three rotations. B) Cumulative impacts over three rotations. Source: *[Schwaiger 2010]*.

With a similar approach Bright et al. *[Bright 2011]* have come to the conclusion that for a boreal forest, the albedo effect of the forest management in addition to the fossil fuel replacement leads to a near-neutral climate system.

At a global level Bala et al. *[Bala 2007]* have simulated the climate impacts of deforestation, including the climate forcing of the CO_2 emitted and the albedo changes. They found that global-scale deforestation has a net cooling influence on Earth's climate because the warming carbon-cycle effects of deforestation are overwhelmed by the net cooling associated with changes in albedo and evapotranspiration.

Latitude-specific deforestation experiments indicate that afforestation projects in the tropics would be clearly beneficial in mitigating global-scale warming, but would be counterproductive if implemented at high latitudes and would offer only marginal benefits in temperate regions *[Betts 2000]*.

Georgescu et al. *[Georgescu 2011]* have shown that the bio-geo-physical effects that result from hypothetical conversion of annual to perennial bioenergy crops across the central United States would have a significant global climate cooling effect, beside the local cooling related mainly to local increases in transpiration, due to higher albedo. They concluded that the reduction in radiative forcing from albedo alone is equivalent to a carbon emission reduction of 78 t C/ha, which is six times larger than the annual biogeochemical effects that arise from offsetting fossil fuel use.

In other studies *[Kulmala 2004]* the analysis has been further expanded to include the emissions of organic carbon (mainly terpenes) from boreal forests, that, besides having an intrinsic cooling effect, act as condensation nuclei for cloud formation, thus enhancing the cloud albedo effect and resulting in additional climate cooling to that of the carbon sink.

Spraklen et al. *[Spraklen 2008]* have quantified the relevance of the cooling effect of organic aerosols emissions and compared it to the warming effect of land surface albedo changes. Using a global atmospheric model they have shown that changes in cloud albedo cause a radiative forcing sufficiently large to result in boreal forests having an overall cooling impact on climate. This is the result of emissions of organic vapours and increased cloud formation due to the increased amount of condensation nuclei (doubled). They conclude that the combination of climate forcings related to boreal forests may result in an important global homeostasis. In cold climatic conditions, the snow–vegetation albedo effect dominates and boreal forests warm the climate, whereas in warmer climates they may emit sufficiently large amounts of organic vapour modifying cloud albedo and acting to cool climate.

In conclusion, for bioenergy production, the climate impact of climate forcers other than CO_2 is still highly uncertain, but in some cases is not at all negligible and therefore should be included in analysis of bioenergy contribution to global warming reduction.

4. Market mediated effects of forest bioenergy

While in Chapter 2 the forest bioenergy GHG LCA is analysed with the attributional life cycle inventory modelling (i.e. the environmental impacts that can be attributed to a system over its life cycle), in this chapter the market mediated impacts of a decision, such as forest bioenergy incentives, will be analysed in terms of GHG emissions. The International Reference Life Cycle Data System *[ILCD 2010]* recommends a Consequential life cycle inventory modelling for the assessment of such market mediated effects.

The consequential life cycle inventory modelling principle aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy, both in the analysed system's background system and on other systems. It models the analysed system around these consequences. The consequential life cycle model is hence not reflecting the actual (or forecasted) specific or average supply-chain, but a hypothetic generic supply-chain is modelled that is forecast along market-mechanisms, and potentially including political interactions and consumer behaviour changes *[ILCD 2010]*.

We have identified the following possible impacts that forest bioenergy incentivisation may cause: displacement of wood for products (or indirect Wood Use Change, iWUC), displacement of wood from other energy sectors (or indirect Fuel Use Change, iFUC), competition for land (indirect Land Use Change, iLUC), management intensification (increased and improved management, fertilization, natural disturbances suppression etc). All these possible impacts shall be addressed if a consequential approach is chosen.

4.1. Displacement of harvested wood products (iWUC)

The consequences of the competition for forest raw materials between bioenergy and the other sectors using wood (sectors in which the wood replaces materials with a typically higher GHG footprint and that would store the carbon out of the atmosphere for a longer time) might be integrated in the forest bioenergy GHG calculation through consequential LCA (as described previously). This consists of an analysis that includes additional economic concepts and requires dynamic market models (instead of the linear and static models of attributional LCA).

As described in section 4.6, Böttcher et al. *[Böttcher 2011]* have used a macroeconomic model to analyze the effect of European energy policies on biomass harvest in European forests up to 2030. They concluded that the total amount of harvested wood will only slightly increase while most of the additional demand for bioenergy will be covered by wood displaced from the wood products market.

Despite avoiding a reduction of the forest carbon stock, this perspective has disruptive effects on GHG emissions and climate change. In fact, wood products have multiple climate mitigation benefits: they increase the anthropogenic carbon pools, they are often much less GHG and energy intensive than similar materials of fossil origin (e.g. concrete, metals etc.) and, finally, bioenergy can be obtained from these products at the end of life to replace fossil fuels and guarantee additional substitution.

A diversion of wood for materials to bioenergy would result either in higher GHG emissions due to the use of more intensive GHG materials (concrete, metals etc.) or in carbon leakage because the wood would have to be produced somewhere else.

Lippke et al. *[Lippke 2011]*, reported the GHG savings obtained per kg of wood used to replace steel and concrete products. These savings are in the range of 2 up to even 10 kg CO_2 eq. saved per kg of wood used when comparing wood joists with steel ones (**Error!**

Reference source not found.). Petersen and Solberg *[Petersen 2005]* found by reviewing Norwegian and Swedish LCAs and substitution effects between wood and alternative materials that when wood replaces steel the savings for each m^3 timber input could be up to 88%, while the corresponding number for concrete replacement is 64% savings.

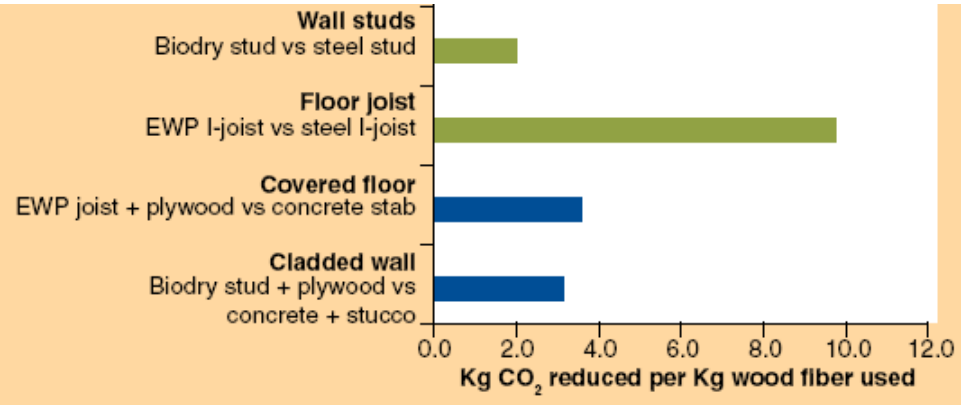

Figure 25: GHG savings when wood derived products are used instead of alternative materials. Source: *[Lippke 2011]*.

Lately, studies have started to focus not only on the steady-state substitution effects of wood products, but rather on the dynamic effects of this carbon sequestration method on climate mitigation. Guest et al. *[Guest 2012]* have re-elaborated the concept of GWP_{bio} (see Section **Error! Reference source not found.**) to include the benefits of carbon storage in wood products. Depending on the storage period and the rotation period of the biomass growth, this type of analysis is able to assign an "actualized" global warming potential to biogenic-CO_2 (**Error! Reference source not found.**). The authors come to the interesting rule of thumb that the GWP_{bio} is roughly zero (no net effect on climate) for biomass which has been stored for approximately half of the growth rotation period. This would imply, for example, that the biogenic CO_2 emissions emitted during the combustion of wood from a boreal forest with a harvesting rotation of 80 years can be assumed to be zero, if the wood is used for wood products and burned after at least 40 years.

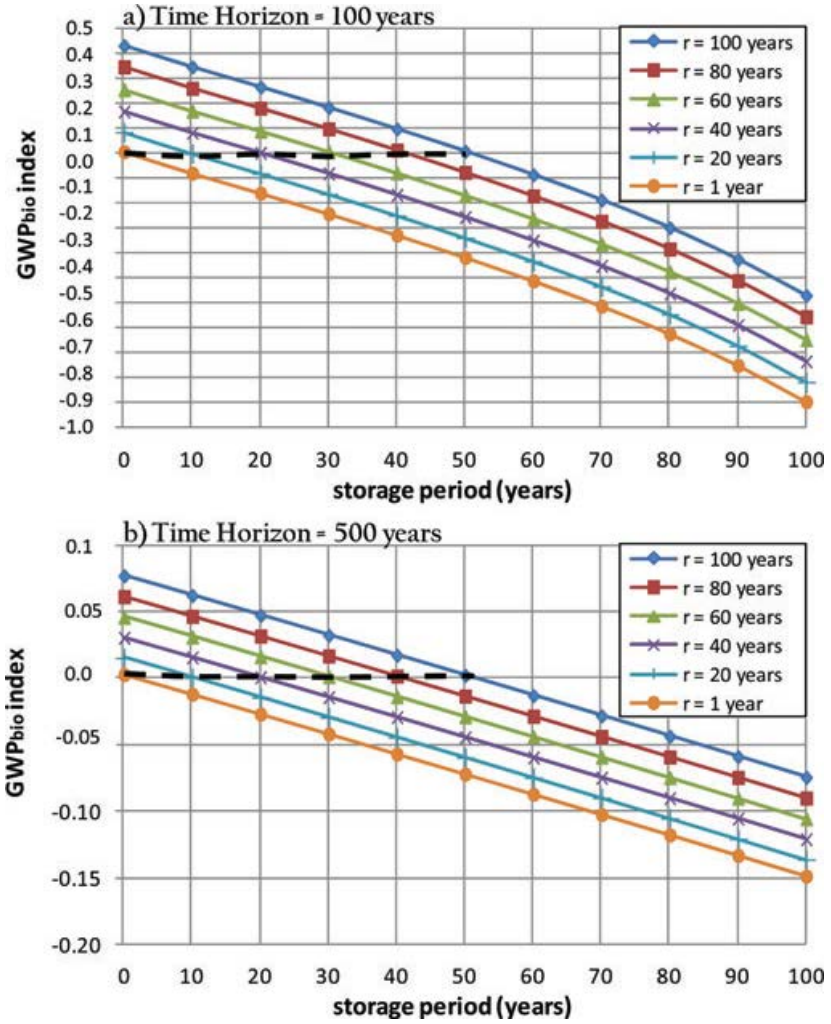

Figure 26: The biogenic global warming potential (GWP_{bio}) factor values for six rotation periods (*r*) as a function of the storage period: (a) 100-year time horizon (TH); (b) 500-year TH. The dotted line (- – -) indicates when the storage period is equal to half the rotation period. Source: *[Guest 2012]*.

Another study from Pingoud et al. *[Pingoud 2012]* uses a similar mathematical approach to calculate the payback time and atmospheric carbon parity point of a wood building with a lifetime of 50 years. They have used the same concept of GWP_{bio} to account for the carbon emissions from the harvest of a boreal stand (80 years of rotation); they have then accounted for the displaced emissions (concrete building and fossil combustion) in another parameter called GWP_{biouse}. The combination of those two parameters produces a curve which assesses the payback time after 23 years and full atmospheric carbon parity after 36 years. This outcome is very close to the one indicated by Guest and coauthors *[Guest 2012]*.

These results indicate that when wood is used in a cascade utilization, then climate mitigation can be achieved in much shorter times than when wood is used purely for energy. Moreover, with the proper measures (longer storage, substitution of C-intensive materials and fossil fuels), the payback time can be even shortened to zero, as compared to centuries indicated for energy-only use.

Studies that fail to consider the wood for material displacement may come to misleading conclusion.

4.2. Displacement of wood from other energy sectors (iFUC)

Competition for forest resources due to increased bioenergy use has been already reported by Schwarzbauer and Stern *[Schwarzbauer 2010]* and Forsström et al. *[Forsström 2012]*.

In the latter study, the authors conclude that increased biofuel production based on woody biomass in Finland would cause an increase in the use of fossil energy in other sectors.

Moreover, an increased use of biomass for bioenergy, even if from sources that are generally considered sustainable such as residues, might indirectly cause changes in harvest levels elsewhere in the world, which could mean an increase in the pressure on natural forests. Many of the wood resources are already used somehow, if they were to be used for bioenergy, they would need to be replaced by other resources with consequences that should be assigned to the GHG balance of the bioenergy itself *[Cowie 2007, Berndes 2012]*.

In a briefing published by the European Parliament Committee on Development *[Wunder 2012]*, the authors state that the impacts of increasing EU demand for wood for energy generation will have macro effects worldwide. The rising demand for woody biomass energy is likely to raise the global price for wood, thus adding pressure on forests and other ecosystems and driving land use conflicts. Risks, direct and indirect, include deforestation when natural forests are replaced by monoculture plantations and long term impacts on local food and energy security in developing countries. However, they recommend when assessing the potential risks of EU's woody biomass demand for local energy security, that an assessment at project level is performed and the analysis is differentiated between countries with a high or low local energy security dependency on woody biomass.

They conclude that conflicts with local energy security are likely to occur if:

- designated sites for the production of woody biomass for export (e.g. energy wood plantations) displace land uses that have a significant role in feeding local energy needs (e.g. open land with trees, orchards etc.) or in ensuring local income.
- woody biomass that currently feeds local energy needs (be it from forest use or from plantations) is redirected to export and hence no longer available for the local population.

They add that regardless of the source of these wood exports, any significant loss in local wood availability is likely to have a negative impact on local energy security, especially in countries where the proportion of the population that depends on woody biomass for its primary energy source is high, such as in Sub-Saharan Africa and developing Asia.

They report, for example, that in Liberia the wood from old rubber trees is now exported to Europe for bioenergy, as it is considered sustainable, being from residues. But Liberian people in urban areas and large towns were relying on charcoal produced mostly from rubber wood. After the starting of this trade, the price of charcoal has gone up about 100% with a serious economic impact and probably an increase of pressure on forests because of the impacts on local energy security *[Wunder 2012]*.

The potential leakage risks associated with the possible effects of residues feedstocks being diverted to biofuels and the potential GHG savings achievable from different processes and feedstocks are still not well addressed and deserve particular attention for future scientific studies.

4.3. Competition for land (iLUC)

Another indirect impact is the appropriation of land for forestry purposes. An additional demand of bioenergy from forests may trigger, via market demand, an expansion of the forested land. Although the direct impact on GHG emissions is positive in case agricultural land is converted, because of the increase in the land carbon stock, the indirect impact of agricultural land diversion should be integrated in the analysis, unless it is on marginal land (abandoned or degraded). An example of how neglecting this impact can lead to misleading conclusions is reported in Sedjo and Tian *[Sedjo 2012]*. They assess the impact of an increased demand of wood for bioenergy with a very simple economic model. They come to the conclusion that the forest carbon stock would increase if the bioenergy demand increases. But they do not comment on the fact the forest carbon stock increases proportionally to the forested area (with a yearly bioenergy demand increase of 2 % the carbon stock doubles in forty years, as well as the forested area, with 4% annual increase in demand, both the carbon stock and the forested land increase six fold). They do not internalize the indirect land use change.

A further example of such an incomplete analysis is reported in Galik and Abt *[Galik 2012]*. They assess the impact of the scale of analysis on the performances of bioenergy systems. They come to the conclusion that if assessed at bigger scale (state, procurement area, land owner) the carbon stock in the forest increases with bioenergy production, while at smaller scales (plot or forest) the carbon stock decreases. But, at the bigger scales, they simulated the market effects while at smaller scale they did not. The implications are that at bigger scale displacement of wood for materials and expansion of the forested area are included. But the indirect emissions due to the production of the displaced wood somewhere else (or with other materials than wood) and the indirect land use change are not accounted for.

The quantitative evaluation of these issues, unfortunately, as with many indirect effects, is extremely difficult and at the current primitive state of the bioenergy market, it is not possible to reach or find conclusive proofs in international literature.

But the impact is expected not to be negligible. According to IEA Bioenergy task 40 “Global wood Pellet Industry Market and Trade Study” *[Cocchi 2011]*, import scenario, in Figure 20,, part of the traded pellets is expected to come from plantations in underdeveloped or developing countries. They expect that that short rotation woody energy crops will likely be established in the same regions as currently pulp plantations are established. Therefore Brazil is by far the country with the largest expected contribution. Other countries would be Uruguay and South Africa. Additionally, it is quite possible that new plantations will be established in the western cost countries of Sub-saharan Africa such Liberia, Sierra Leone and Ghana.

4.4. Rebound effect and competition among renewables

The reports and scientific papers reviewed make the assumption that each unit of energy supplied by renewable sources replaces a unit of energy from fossil fuel sources. But because of the complexity of economic systems and human behaviour, often changes aimed at reducing one type of resource consumption, either through improvements in efficiency of use or by developing substitutes, do not lead to the intended outcome when net effects are considered. The range of mechanisms that lead to this outcome are commonly grouped under the heading of rebound effect.

The rebound effect is the increased consumption of energy services following an improvement in the efficiency of delivering those services. This increased consumption may offset part of the energy savings that may otherwise be achieved. The rebound effect is generally expressed as a ratio of the lost benefit compared to the expected environmental benefit when holding consumption constant. For instance, if a 5% improvement in vehicle fuel efficiency results in only a 2% drop in fuel use, there is a 60% rebound effect (since (5-2)/5 = 60%). The 'missing' 3% might have been consumed by driving faster or further than before.

This approach has been widely used to assess the effects of increased energy efficiency *[Sorrell 2007; Greening 2000, Druckman 2011].*

Many recent studies have assessed that the substitution effect may be significantly less than 1 *[Chen 2012; Drabik 2011; Hochman 2010; Rajagopal 2011; Thompson 2011; York 2012]*. York *[York 2012]* showed that the average pattern across most nations of the world over the past fifty years is one where 1 MJ of total energy use from non-fossil sources (hydropower, nuclear, geothermal, solar, wind, tidal and wave energy, combustible renewables and waste) displaced less than 0.25 MJ of fossil fuel. Focusing specifically on electricity, each MJ of electricity generated by non-fossil fuel sources displaced less than 0.1 MJ of fossil fuel electricity.

These results are still controversial and disputed, but, if they were correct, they would have policy implications. They would imply that many of the policies aimed at suppressing the use of fossil fuel should not focus only on developing other energy sources but should also take into account additional economic and social concepts.

Another issue is that normally the competition among renewables for incentives is considered beneficial as it may lead to economic competition, thus, to lower cost for the incentives. Regulatory frameworks may be implemented in such a way that subsidizing the construction of a plant for the production of electricity from stemwood from dedicated bioenergy harvest (the bioenergy scenario with longer payback times) may displace a plant based on other renewables. In many countries the renewable energy sources are supported with Green Certificates schemes that actually favour competition among renewables while the total share of renewables is fixed. An example is provided by the Italian new system of incentives for renewables that will enter into force in 2013. The Decreto 6 luglio 2012 (Ministero dello Sviluppo Economico) *[DM 6 luglio 2012]* provides incentives as feed in tariffs with a lowest bid auction. The different types of biomass compete among them and with biogas and biofuels. This is rather common in all the renewable incentives schemes and may result in pellets from stemwood from bioenergy dedicated harvest displacing renewables with much shorter payback times (PV, wind, biogas from manure, etc.). In general this is valid throughout Europe, being the renewable share of 20% mandatory, if a source of energy is not considered eligible because of sustainability criteria, it has to be replaced by another renewable energy source.

4.5. Intensified management & natural disturbances

The higher market value of wood due to bioenergy incentivisation may lead to forest management intensification aimed at increasing the forest productivity. Excluding afforestation (dealt with in section 4.3), an increase in woodfuel production may be attained with natural disturbances suppression, management optimisation (thinnings, stands density etc), changes in species, fertilization, irrigation and so on.

Fertilization and management optimization (higher densities, faster growing species etc.) could sensibly reduce the payback time *[Alam 2011; Routa 2011; Trømborg 2011, Jonker 2013]*. However, studies that quantify the effects of an increased wood price due to bioenergy production on the implementation of such management improvements are not yet available.

A rough estimate on fertilization is provided by the Swedish University of Agricultural Sciences in their website. They report that in Sweden around 60 000 hectare of forest land are fertilized each year (about 0.3% of the productive forested area) and that the fertilized forest area in Sweden may increase, but hardly more than double because not all forests are worth fertilizing. On fertile land there is no effect from fertilization *[SLU 2012]*. A further estimate is provided by Fox et al *[Fox 2006]* that reports, for the US South East pine plantations, a share of fertilized area lower than 4%,

In forest management, the natural disturbances considered are wildfires, pests outbreaks and windthrow. These disturbances can cause partial loss of the carbon in the forest. This aspect is reported in this section of market mediated impacts because it is often claimed that an increased use of biomass for bioenergy may cause an increase in the forests value resulting in an incentive for forest owners to improve the forest management and fight natural disturbances.

Hudiburg et al. *[Hudiburg 2011]* have simulated the impact of different forest management practices on the GHG reduction potential of forests in the US West Coast. The four scenarios analyzed were: Business As Usual (preventive thinning and harvest), adding fire prevention practices to the BAU (increased removal of fuel ladders), making fuel ladder removal economically feasible by emphasizing removal of additional marketable wood in fire-prone areas (economically feasible), or thinning all forestland to support energy production while contributing to fire prevention (bioenergy production). Removals are in addition to current harvest levels and are performed over a 20-year period such that 5% of the landscape is treated each year.

They have demonstrated that even in an area with high wildfire risk, the harvest of wood for energy purposes is beneficial to reduce GHG emissions only in extreme conditions (e.g. if the sink capacity is jeopardized by insect infestations, increased fire emissions, or reduced primary production) (**Error! Reference source not found.**).

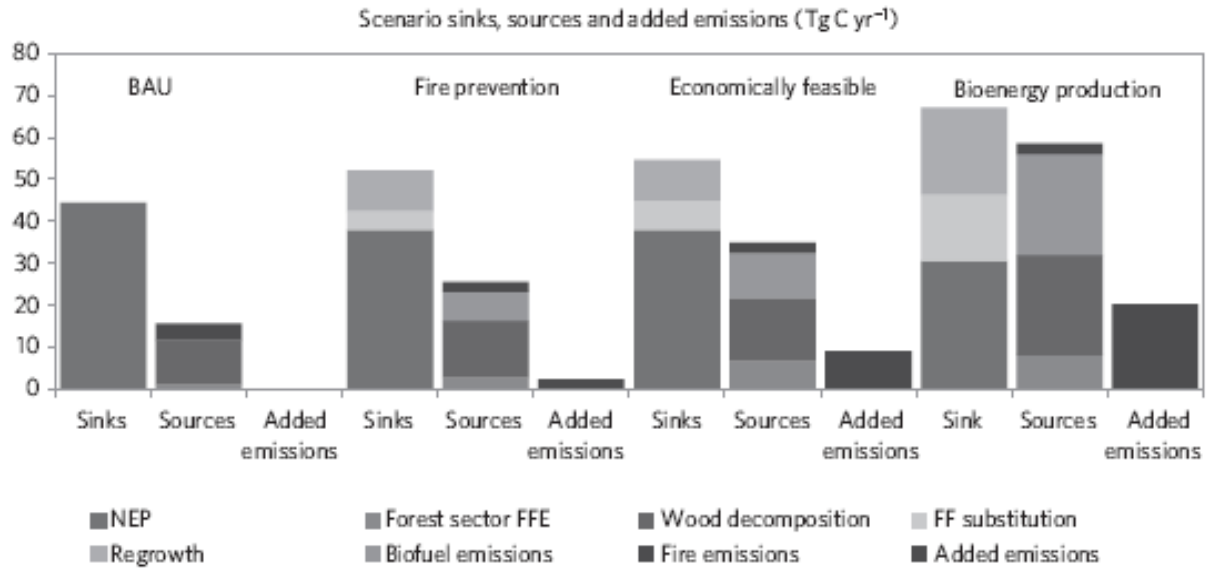

Figure 27: Total US West Coast forest sector carbon sinks, sources and added emissions relative to BAU under various management scenarios. Units are in Tg C yr^{-1}. Life cycle assessment estimates account for changes in carbon on land in addition to emissions associated with production, transport and usage of wood, and substitution and displacement of fossil fuel emissions associated with use and extraction. BAU results in the lowest anthropogenic emissions from the forest sector. Source: *[Hudiburg 2011]*.

On the other hand, Lippke et al. *[Lippke 2011]* have reported that the fire risk is increasing in the unmanaged forests in the drier interior regions of US, mainly because of a century of fire suppression measures which resulted in unnatural overly dense stands, and the impact of global warming. Despite this increased risk of fire, the carbon stock could continue to increase assuming 20th century fire rates. Models that project a doubling of fire rates due to global change, essentially cap the carbon that would be stored in the forest.

The high fire rates of the beginning of the 21st century, however, suggest that these forests might have already become a carbon source (**Error! Reference source not found.**).

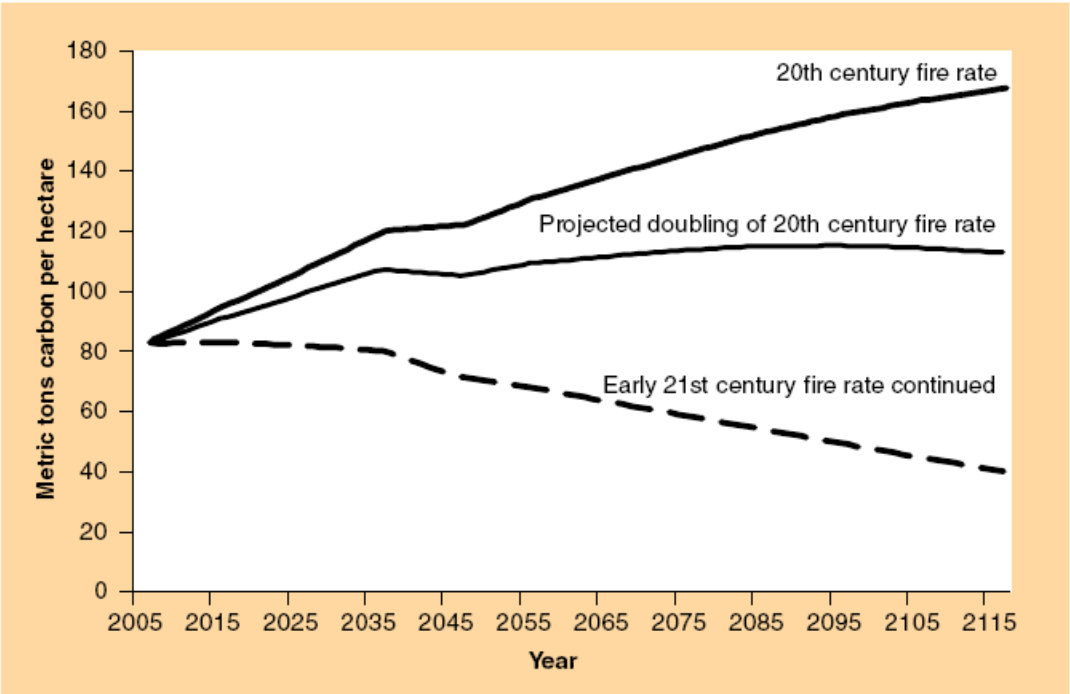

Figure 28 : The impact of fire rates on carbon for inland northwest national forests (Idaho, Montana and Washington east of the Cascades). Source : *[Lippke 2011]*.

Lippke et al. *[Lippke 2011]* conclude that without more aggressive fire risk reduction and investment in reforestation of currently burnt sites, many more unmanaged U.S. interior forests will probably become emission sources rather than carbon sinks, resulting in loss of the opportunity to offset fossil-intensive products.

Other modelers *[Campbell 2011; Mitchell 2012]*, on the contrary, have concluded that wildfires have a limited impact on biomass longevity and even if wildfires may temporarily lower the C storage of the landscape, most of the losses occur among un-harvestable components of the forest, such as leaf litter and fine woody debris. Most of the harvestable biomass remains unconsumed even by high-severity wildfires and can either be salvage harvested shortly thereafter or persist on the landscape for decades.

Mitchell et al. *[Mitchell 2009]* calculated also the payback time of several wildfire prevention measures on two types of forests. The conclusions, for these specific forests, indicate that wild fire fuel reduction treatments should be forgone if forest ecosystems are to provide maximal amelioration of atmospheric CO_2 over the next 100 years (**Error! Reference source not found.**).

Fires might have impacts also on the soil carbon. Johnson and Curtis *[Johnson 2001]* have found significant differences among fire treatments, with the counterintuitive result of lower soil C amounts resulting from prescribed fire and higher soil C following wildfires. The latter result is attributed to the sequestration of charcoal and recalcitrant, hydrophobic organic matter and to the effects of naturally invading, post-fire, N-fixing vegetation.

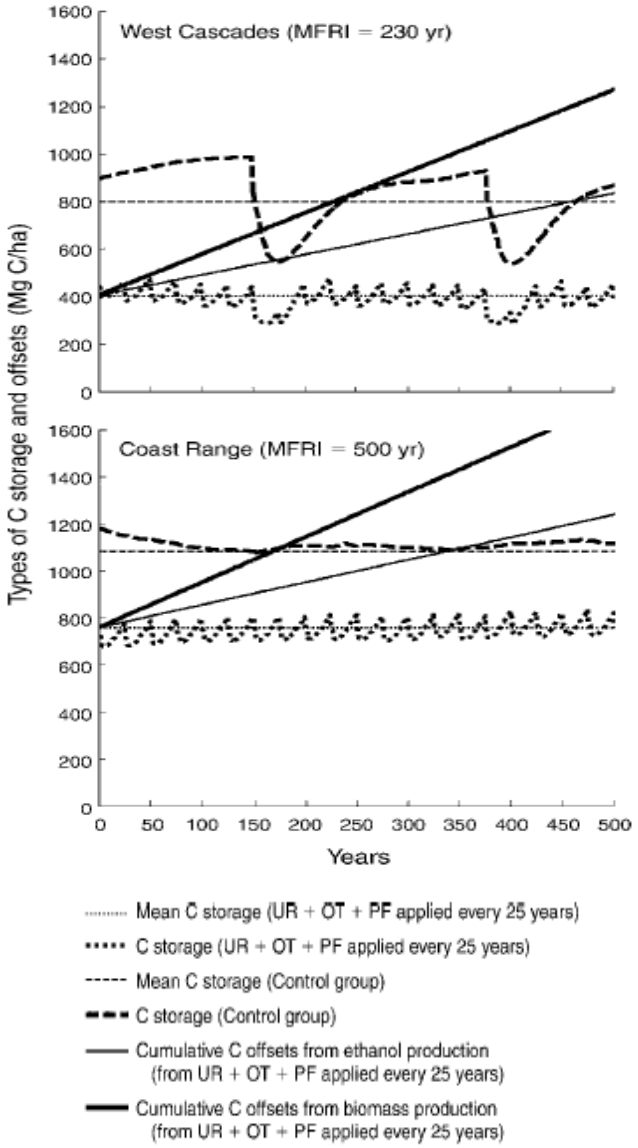

Figure 29: Time series plots of C storage, mean C storage, and biofuels offsets for control groups and fuel reduction treatment UR + OT + PF (understory removal + overstory thinning + prescribed fire) applied to a second-growth forest every 25 years for the west Cascades and Coast Range. East Cascades simulations were excluded from this plot because there was little or no trade-off incurred in managing these forests for both fuel reduction and C sequestration. Source: *[Mitchell 2009]*.

In conclusion, results on the effects of natural disturbances (wild fires, pests outbreaks, and windthrow) are very scattered and it is difficult to reach meaningful conclusions. Being unpredictable events, it is complicated to include the occurrence of disturbances in forest GHG savings potential calculation and distinguish the relative impact on the bioenergy and reference scenarios. However, after disturbances (for the wildfires depending on the severity) most of the biomass harvestable for bioenergy purposes would remain in the forest and can either be salvage-harvested or remain in the forest for decades.

4.6. Large scale techno-economic modeling

This type of analysis includes a macroeconomic model that estimates the developments of the wood market in terms of imports, quantity of wood used for wood products and for bioenergy etc. as response to a given decision.

The market model is coupled with a forest model that can model changes in carbon stocks in all the pools of forests (including living and dead wood, soil-C etc.) and eventually the carbon stocked in wood products.

These two models can then be combined with several scenarios for the substitution of wood products in which a typical LCA (biogenic-CO_2 emissions are set to zero) is applied to calculate the GHG savings due to the use of biomass compared to the alternative materials / feedstocks. The combination of these calculations would provide a clear and quantitative forecast of possible carbon savings or emissions due to different policy scenarios and over different time horizons.

This method has been already used in the study by the United Nations Economic Commission for Europe (UNECE) and the Food and Agriculture Organization (FAO) in the European Forest Sector Outlook Study II (EFSOS) *[UNECE 2011]*, where an analysis of the effects of the implementation of two policy scenarios, one aiming at maximizing the carbon sequestration by forests and products and the other promoting bioenergy for fossil fuel substitution, is implemented.

The first scenario (maximizing biomass carbon) results in an increase of carbon sequestration and substitution of 50 TgC/y compared to the reference system (IPCC B2 storyline). The second scenario (promoting the use of wood for bioenergy) results in an increase of carbon uptake and substitution of only 20 TgC/y (Table 10).

In the same study it is recommended that in order to maximize the forest sector's contribution to climate change mitigation, the best strategy is to combine forest management focused on carbon accumulation in the forest with a continuous flow of wood for products and energy. In the long term however, the sequestration capacity limit of the forest will be reached, and the only potential for further mitigation is regular harvesting, to store the carbon in harvested wood products or to avoid emissions from non-renewable materials and energy sources *[Ximenes 2012]*.

Furthermore, UNECE-FAO recommend a 'cascaded' use of wood (i.e., firstly for wood-based products, secondly recovered and reused or recycled and finally used for energy).

Table 10: Carbon stocks and flows in the EFSOS scenarios, total Europe. (Source: The European Forest Sector Outlook Study II *[UNECE 2011]*)

		Unit	Reference		Maximising biomass carbon	Promoting wood energy
			2010	2030	2030	2030
Carbon stock	Forest biomass	Tg C	11508	13214	14130	13100
	Forest soil	Tg C	14892	15238	15319	14994
Carbon flows	Change in forest biomass	Tg C/yr		85.3	131.1	79.6
	Change in forest soil	Tg C/yr		17.3	21.4	5.1
	Net change in HWP	Tg C/yr		18.2	18.2	17.6
Substitution effects	For non-renewable products	Tg C/yr	NA	NA	NA	NA
	For energy	Tg C/yr	61.6	83.0	83.0	121.7
Totals	Stock (forest only)	Tg C	26400	28452	29449	28093
	Flow (sequestration + substitution)	Tg C/yr		203.7	253.6	224.0

Another study at European level is provided by Böttcher et al. *[Böttcher 2011]*. In their article they assess tradeoffs of bioenergy use and carbon sequestration at large scale and describe the results of the comparison of two advanced forest management models that are used to project CO_2 emissions and removals from EU forests until 2030. *EFISCEN*, a detailed statistical matrix model and *G4M*, a geographically explicit economic forestry model, use scenarios of future harvest rates and forest growth information to estimate the future carbon balance of forest biomass. They assessed two scenarios: the EU baseline scenario and the EU reference scenario (that includes the national renewable targets of EU member states for 2020).

The results in Figure 30 show that the European total domestic wood harvest is forecasted to increase slightly in 2020 in the reference scenario (including the RED policies) compared to the baseline (no RED) and most of the domestic wood production is diverted from the materials sector (furniture, building, pulp and paper) to bioenergy. The impacts of reaching the EU objectives are a further decrease in the forest sink compared to the baseline in the medium run (until 2020) by 4–11% (or 10–30 Mt CO_2, the order of magnitude of annual emission of countries like Croatia or Slovenia) .

This effect is currently not accounted for in the EU policy, as the emission reduction target of 20% excludes land use emissions and removals *[Zanchi 2010; Zanchi 2011; Bird 2011; Böttcher 2011]*.

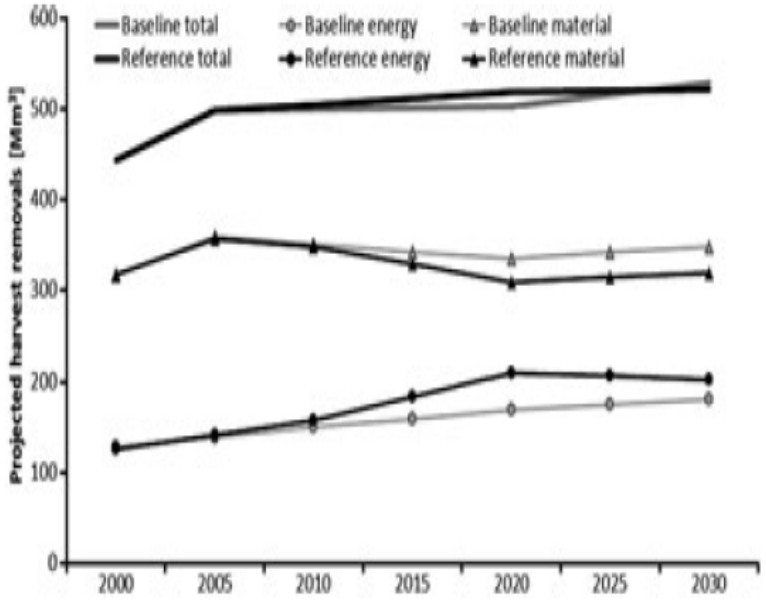

Figure 30: Baseline and reference projection of domestic wood production (overbark) for EU-27 countries for energy and material use (including sawnwood, pulp wood and other industrial roundwood). Source: *[Böttcher 2011].*

In order to address this issue the EC published in 2012 a communication entitled 'Accounting for land use, land use change and forestry (LULUCF) in the Union's climate change commitments' *[COM(2012) 94]* that reports that the sink in the LULUCF sector is projected to decrease in the EU by 2020 under a BAU scenario ("Business as Usual" assumes that Member States will reach their 20% reduction targets).

For the LULUCF sector as a whole, in the same document is reported a forecast of a decline of about 10% in 2020 compared to the period 2005 – 2009, equivalent to emitting 33 Mt CO_2 more per year.

The decrease is expected to be very pronounced in forest management, for which net CO_2 removals are expected to fall by about 60 Mt CO_2, i.e. roughly the equivalent to the total greenhouse gas emissions of Bulgaria, Denmark, Ireland or Sweden in 2009. This is partly compensated by the plantation of forests (afforestation) *[COM(2012) 94]*.

At country level an interesting study on Finland was presented at the 20th European Biomass Conference by the Finnish Forest Research Institute *[Kallio 2012]*. They have analyzed two bioenergy scenarios: LowBio (stagnating use of bioenergy at 2010 level) and HighBio, (2020 EU bioenergy targets met substituting fossil diesel and peat/coal). They combined two models: a spatial partial equilibrium model for the Finnish forest sector and a regionalized forest simulations model. The study concluded that reaching the RES targets would cause a net increase in CO_2 emissions. This is not due to the absolute reduction of the forest carbon stock, but to the reduction of the carbon sink (as shown in **Error! Reference source not found.** and **Error! Reference source not found.**).

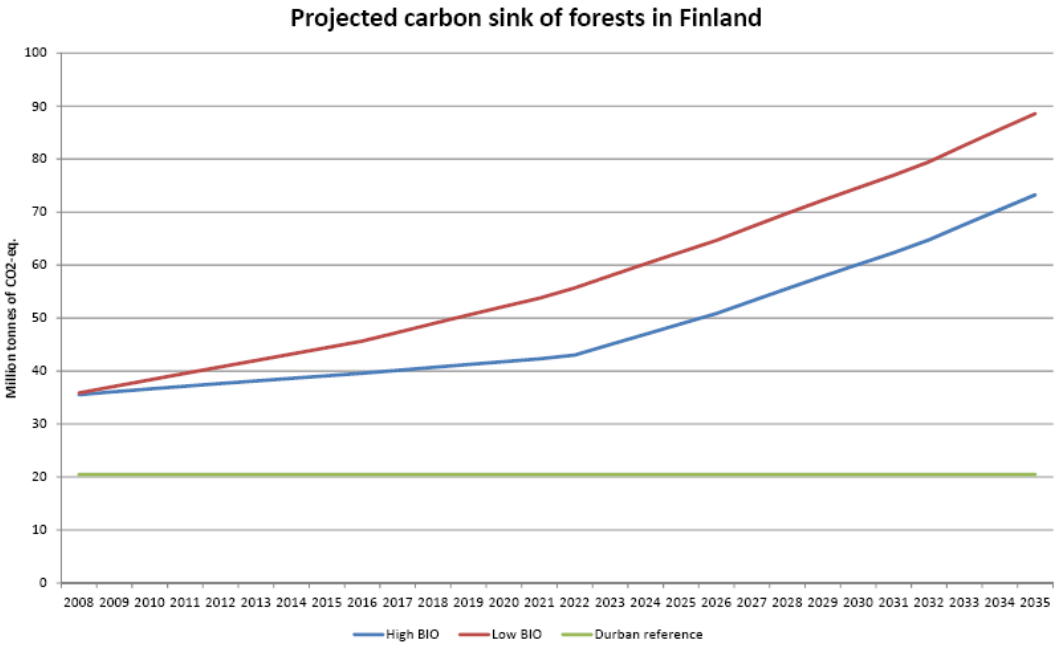

Figure 31: Projections of forest carbon sink in Finland up to 2035: LowBio = stagnating use of bioenergy at 2010 level; HighBio = 2020 RED bioenergy goals met. Source: *[Kallio 2012]*.

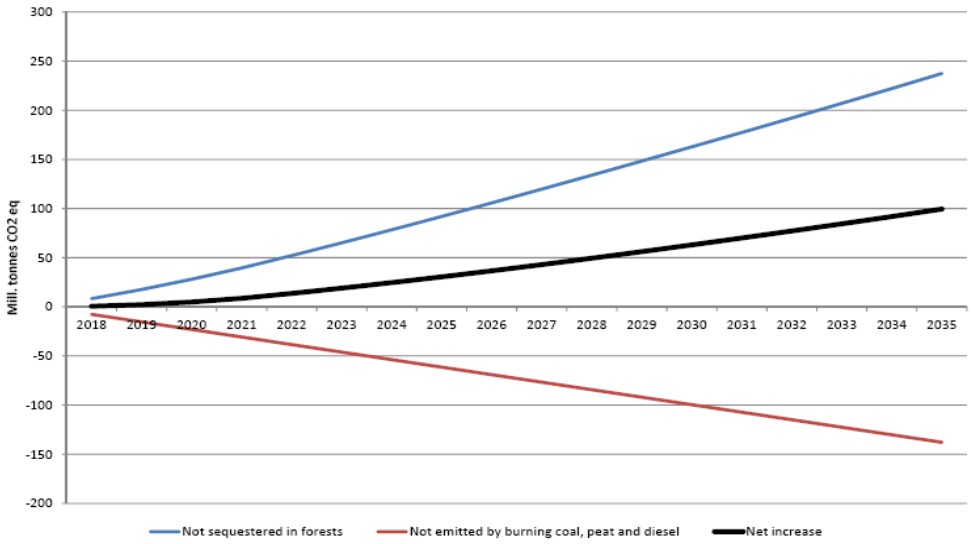

Figure 32: Relative (HighBio-LowBio) cumulative CO_2 emissions in Finland by 2035 : LowBio = stagnating use of bioenergy at 2010 level; HighBio = 2020 RED bioenergy goals met; Source: *[Kallio 2012]*.

In France Lecocq et al. *[Lecocq 2011]* compared the environmental and economic implications for the French forest sector of a "stock" policy (payment for sequestration in situ), a "substitution" policy (subsidy to fuelwood consumption), and a combination thereof – all calibrated on the same price of carbon. They used the French Forest Sector Model (FFSM), which combines a dynamic model of French timber resources and a dynamic partial-equilibrium model of the French forest sector. Simulations over the 2010–2020 period show that the "stock" policy is the only one that performs better than business-as-usual in terms of CO_2 emissions (**Error! Reference source not found.**).

Table 11: Changes in carbon stock in standing forests, cumulative substitution effect, and total carbon stock in 2020 relative to reference ($MtCO_2$). By convention, (+) signs refer to net absorptions (i.e., less carbon in the atmosphere) and (–) signs refer to net emissions (i.e., more carbon in the atmosphere). Source: *[Lecocq 2011]*.

[Mt CO_2]	Substitution policy (S1)	Stock Policy (S2)	Combination (S3)
Carbon stock in standing forests in 2020	-7.1	+0.9	-6.1
Cumulative substitution effect 2010-2020	+3.7	-0.05	+3.6
Net carbon balance in 2020	-3.4	+0.85	-2.5

In the U.S., Nepal et al. *[Nepal 2012]* have modeled the U.S. forest sector's projected capacities for carbon sequestration in response to the use of forest resources for energy. The study shows that the IPCC A1B Scenario (16-fold increase by 2060 of wood energy consumption) would convert U.S. timberlands to a substantial carbon emission source by 2050. In contrast, the same high growth in the economy coupled with much smaller expansion of U.S. wood biomass energy consumption (HFW – historical fuelwood consumption with less than two-fold increase by 2060) would result in a projected increase in the average annual additions to the U.S. forest sector carbon by up to four-fold by 2060 (see Figure 33). The credits for the fossil fuel displaced are not accounted for, thus the net effect of the bioenergy choice is not reported, but the difference in the two scenarios has to be allocated to the bioenergy production..

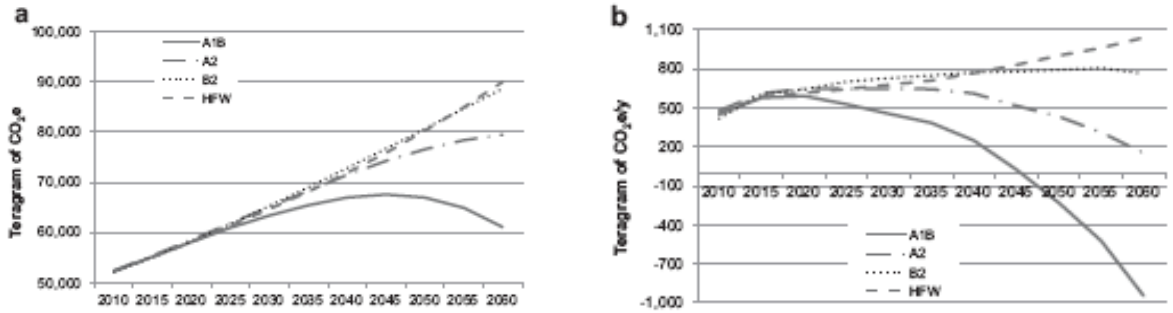

Figure 33: Projected total U.S. tree biomass carbon (a) stock (Tg CO2e) and (b) flux (Tg CO2e/y) for A1B, A2, B2, and HFW scenarios during 2010e2060. Source: *[Nepal 2012]*.

There are inevitable uncertainties linked to the assumptions used in such models. However these tools, based on scenario analysis, allow an appropriate evaluation of the possible effects of different policies.

5. Further research

In the assessment of the global warming mitigation performances of specific forest bioenergy pathways, it is necessary to identify and fill the gaps in the different developed methodologies, and reach an agreement on a common, comprehensive and scientifically sound LCA methodology.

As it is usual in the LCA studies of many products and services, data availability and standardization are fundamental to reach sound and reproducible conclusions. In this respect, it is useful to further investigate the fluxes of forest carbon and the impacts of management changes in the different scenarios analyzed on all the forest carbon pools.

The need for a better understanding of the indirect impacts should not be ignored. The correlation with the displacement in other sectors (especially in wood industry) due to additional demand of wood for bioenergy, and how this displacement is recovered have not yet been clearly quantified. Besides that, even within the energy sector, whether and how wood exports are likely to impact on local energy security is not yet understood, especially in those countries where the population depends on woody biomass for its primary energy, and thus pressure on forests may indirectly increase.

On the other hand, the uncertainties in the climate impacts of most of the climate forcers, (aerosols, ozone precursors, albedo, evapotranspiration and clouds cycle), result in a large spread of the results. As their climate impact in some cases may be of the same order of magnitude of CO_2 (for which, on the other hand, the accounting is rather straight forward), a better understanding of how these forcers affect the climate is needed.

For a better understanding of the climate impact of bioenergy from forests at large scale (fundamental for policy assessment), the best approach is the development of a global advanced forest management model, able to project GHG emissions and removals from world forests in the long term in reaction to specific policy inputs.

The model should have the following characteristics:

- worldwide coverage with site-specific conditions for forestry;
- long term modeling capacity (centuries);
- include both the markets for harvested wood products and for energy;
- account for the effects of all the climate forcers (long-lived GHG, short-lived GHG, aerosols and albedo, evapotranspiration);
- being able to model all the carbon pools in the forest (including the risk of disturbances) and out of the forest (displacement from other sectors, such as food, fibers and feed);
- be based on data from sound macroeconomic and sector specific market models capable of modeling also the rebound effect.

Therefore, beside the need for a scientifically sound and shared methodology for the assessment of the climate impacts of bioenergy, the most important contribution required to future research is the provision of more background data (especially on indirect impacts) and the reduction of uncertainties in the climate impacts of other forcers than CO_2.

6. Conclusions

Within this study, a large number of peer reviewed publications and reports have been reviewed in order to understand the consequences of increased forest bioenergy production on GHG emissions.

Most of the forest feedstocks used for bioenergy, as of today, are industrial residues, waste wood, residual wood (thinnings, harvest residues, salvage loggings, landscape care wood etc.) for which, in the short to medium term, GHG savings may be achieved. On the other hand, in the case of stemwood harvested for bioenergy purposes only, if all the carbon pools and their development with time are considered in both the bioenergy and the reference fossil scenario, there is an actual increase in CO_2 emissions compared to fossil fuels in the short-term (few decades). In the longer term (centuries) also stemwood may reach the fossil fuel parity points and then generate GHG savings if the productivity of the forest is not reduced because of bioenergy production.

There is a large variability in the literature results for fossil fuel parity times. This is due to differences in the characteristics of the forest system considered (growth rate, management), in the carbon pools included, in the system boundaries definition and in the reference baseline used in the analysis. Although all these parameters play a relevant role in the calculations, the studies reviewed can be summarized in a qualitative way (**Error! Reference source not found.**).

Table 12: Qualitative evaluation of the papers reviewed. Source: own compilation JRC.

Biomass source	CO_2 emission reduction efficiency					
	Short term (10 years)		Medium term (50 years)		Long term (centuries)	
	coal	natural gas	coal	natural gas	coal	natural gas
Temperate stemwood energy dedicated harvest	---	---	+/-	-	++	+
Boreal stemwood energy dedicated harvest	---	---	-	- -	+	+
Harvest residues*	+/-	+/-	+	+	++	++
Thinning wood*	+/-	+/-	+	+	++	++
Landscape care wood*	+/-	+/-	+	+	++	++
Salvage logging wood*	+/-	+/-	+	+	++	++
New plantation on marginal agricultural land (if not causing iLUC)	+++	+++	+++	+++	+++	+++
Forest substitution with fast growth plantation	-	-	++	+	+++	+++
Indirect wood (industrial residues, waste wood etc)	+++	+++	+++	+++	+++	+++

+/-: the GHG emissions of bioenergy and fossil are comparable; which one is lower depends on specific pathways,

-; --; ---: the bioenergy system emits more CO_2eq than the reference fossil system

+; ++; +++-: the bioenergy system emits less CO_2eq than the reference fossil system

**For residues, thinning & salvage logging it depends on alternative use (roadside combustion) and decay rate*

The results attained are strongly correlated with the following parameters: the fossil fuel replaced, efficiency of the biomass utilization, the future growth rate of the forest, the frequency and intensity of biomass harvests and the initial landscape carbon stock.

Bioenergy production affects the climate also through market mediated effects. Large scale, techno-economic models indicate that an increased forest wood removal for bioenergy purposes causes either a decrease of the forest carbon stock (or a lower increase compared to the reference fossil system) or a displacement of wood for products.

Beside the displacement of raw materials from carbon intensive sectors (such as buildings), forest biomass for bioenergy may be sourced from other energy systems, which then may have to replace the raw materials with more GHG intensive energy sources.

It is also worth noting that most of the studies analysed assume that the growth rate of the forest that follows the harvest does not change in the next rotation. However, the increased bioenergy demand may lead (through market effects) to changes in forest management (thinning instead of clearcuttingsetc, more productive species, natural disturbances prevention, fertilization etc.) that could mitigate the forest carbon losses. Large scale techno-economic quantitative studies analyzing these impacts are not yet available.

Bioenergy production may cause also competition for land. GHG savings are quickly achieved by new plantations if no iLUC is caused (e.g. new plantations on marginal or degraded land). But since many studies report that the expansion of SRF is expected to be more relevant in developing countries, this may directly trigger additional pressure on forests or cause iLUC .

Normally the comparison with the fossil system is performed with a substitution factor of 1 (1 MJ bioenergy replaces 1 MJ fossil), but the introduction of an additional source of energy in the energy market may cause a rebound effect due to the energy price reduction that triggers an increase in consumption that reduces the substitution factor.

For what concerns the effects of natural disturbances (wild fires, pests outbreaks, and windthrow) the results are very scattered and it is difficult to reach meaningful conclusions. Being unpredictable events, it is complicated to include the occurrence of disturbances in forest GHG savings potential calculation and distinguish the relative impact on the bioenergy and reference scenarios.

For a proper accounting all the above market mediated impacts have to be accounted for when assessing the GHG mitigation potential of bioenergy in comparison to the fossil reference with a consequential modeling approach.

It must be stressed also that the timeframe of the comparison has a significant influence on the performances of the reference system. If the timeframe chosen is short (within a decade), the current emissions from the reference fossil system can be considered appropriate and constant for the comparison. In the case of a long-term analysis (several decades or centuries) though, also the changes in the reference fossil scenario have to be accounted for (both in the forest and the energy system). For instance, in practically all of the studies analyzed the reference fossil system (coal or NG) is kept constant and unchanged for the whole duration of the analysis (even centuries), while, according to EU policies, by 2050 the EU should be decarbonized, implying that future savings might be much smaller than current ones. On the other hand there is an increase in the use of fossils fuels with higher GHG emissions (shale gas, tar sands etc.). These changes in the reference scenario may affect the fossil fuel parity times.

The uncertainty associated with the carbon accounting in the results reported is limited, but, if other climate forcers (albedo and short lived GHG) were included in the analysis, such

uncertainty would increase dramatically and the impacts would become strongly dependent on the local condition. At the moment the large variability in the estimation of these climate forcers is still hindering a systematic inclusion of these effects in scientific and policy evaluations.

This review has shown that in the life cycle assessment of forest bioenergy it is fundamental to: integrate the carbon stock changes in all the carbon pools (inside and outside the boundaries of the forest for the whole duration of the analysis and for both the bioenergy and reference fossil scenarios). In case a consequential approach is chosen, all of the market mediated effects should be included in the analysis (products and energy displacement, competition for land, intensified management).

Considering all the above, the challenges posed by the forest bioenergy sector and its influence on climate are exceptionally complex and long-term, and require improved understanding especially in the quantification of market mediated effects and impacts of other climate forcers.

Concluding, from the studies analyzed it emerges that in order to assess the climate change mitigation potential of forest bioenergy pathways, **the assumption of biogenic carbon neutrality is not valid under policy relevant time horizons (in particular for dedicated harvest of stemwood for bioenergy only) if carbon stock changes in the forest are not accounted for.**

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Abstract
Via a detailed analysis and review of the currently available literature, this work aims at clarifying the phenomena, physical and mathematical, underpinning the methodologies and results in forest bioenergy carbon accounting.
The large scale techno-economic models indicate that an increased forest stemwood removal for bioenergy purposes may cause either a decrease of the forest carbon stock (or a lower increase compared to the BAU) or displacement of wood for products.
The calculation of biogenic CO_2 correction factors or payback times provides results with a large range of variability that depends on the many different characteristics and assumptions on both the bioenergy system and the reference fossil system such as: the fossil fuel replaced, efficiency of the biomass utilization, the future growth rate of the forest, the frequency and intensity of biomass harvests, forest management, the initial landscape carbon stock. However, in most cases, the dedicated harvest of stemwood for bioenergy causes an actual increase in CO_2 emissions compared to fossil fuels in the short-term (decades). In the long-term eventually it may generate GHG savings and become carbon neutral (from several decades to centuries).
It can be concluded also that the carbon neutrality assumption for forest bioenergy may be misleading and it is fundamental to integrate all the carbon pools in the analysis (above ground biomass, below ground biomass, dead wood, litter, soil and harvested wood products) and their evolution in the time horizon of the analysis for both the bioenergy scenario and the counterfactual. A comprehensive evaluation of the climate impacts of dedicated harvest of stemwood for bioenergy has to integrate also all of the climate forcers (aerosols, ozone precursors and albedo).

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