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CICLO: XXVII

TITOLO TESI: EVALUATION OF THE ENVIRONMENTAL IMPACTS OF WOOD PRODUCTS  
FOR BIO-ENERGY THROUGH LIFE CYCLE ASSESSMENT (LCA)

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*To Oni's*



## Foreword

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## **Abstract**

The use of wood for energy has grown in the last years as an alternative to fossil fuels. National and international laws promote the use of wood in the policies for the mitigation of climate change, based on the assumption that wood has a neutral carbon balance because the combustion emissions are offset by the absorption in forest (assumption of carbon neutrality). However, this assumption does not take into account the emissions associated with the life cycle of the product, e.g. related to processing and transporting biomass. In addition there is a time lag between the release of CO<sub>2</sub> during combustion and its absorption in forest and this could have an impact on global warming.

The objectives of this research project are: 1) to assess the environmental impacts of wood products through Life Cycle Assessment (LCA); 2) to include the dynamics of forest carbon sequestration and natural decomposition of woody biomass in LCA. The research is conducted by means of two case studies: the first is the LCA of firewood in the Northern East Italy; the second concerns the production of wood chips in the Pacific Northwest in the United States. This dissertation consists in eight chapters. Chapter 1 describes the legislative framework and the state of the art of the international experiences and research projects on the subject. A review of literature studies was conducted highlighting the main limitations and defining the research objectives. Chapters 2 and 3 analyze the supply chain of wood products for bioenergy, providing reference data for the biomass extraction and production processes, the physico-chemical properties of wood and the LCA methodology, in terms of standards, databases, softwares and methodologies. Chapters 4 and 5 present the results of the two case studies which identify the transportation to be the critical phase of LCA, in the case of firewood related to the importation of raw materials from abroad, in the case of chips related to the transportation on forest road. Chapter 6 deals with the assessment of carbon sinks and stocks in the study areas previously analyzed. In Chapter 7 we face the problem of how to include forest carbon sequestration within the LCA. This led to the development of a methodology to perform a "dynamic LCA", which, in Chapter 8, is applied to a case study in the Pacific Northwest. The methodology is based on the use of radiative forcing to evaluate the impact of emissions and absorption sources on climate change. The results show that, in the case study considered, a "Radiative Forcing Turning Point" exists, i.e. a point located approximately in the middle of the forest rotation period (from 17 to 21 years old), where the life cycle impacts are compensated by carbon dioxide absorption and beyond which the biomass produces a net benefit in the carbon balance. The development of a dynamic LCA is very innovative in the context of LCA and allowed to discuss the veracity of the assumption of carbon neutrality.





## Riassunto

L'uso di prodotti legnosi per fini energetici è cresciuto negli ultimi anni come alternativa ai combustibili fossili. Leggi nazionali e internazionali promuovono l'uso del legno nell'ambito delle politiche di mitigazione dei cambiamenti climatici, basandosi sull'assunzione che il legno abbia un bilancio di carbonio nullo, in quanto le emissioni rilasciate dalla sua combustione vengono compensate dagli assorbimenti in foresta (assunzione di carbon neutrality). Tuttavia, questa assunzione non tiene in considerazione le emissioni associate al ciclo di vita del prodotto, e.g. alla lavorazione e al trasporto della biomassa. Inoltre c'è uno sfasamento temporale tra il rilascio di CO<sub>2</sub> nella combustione e il suo assorbimento in foresta e questo potrebbe avere conseguenze sul global warming. Gli obiettivi di questo progetto di ricerca sono: 1) valutare degli impatti ambientali dei prodotti legnosi attraverso Life Cycle Assessment (LCA); 2) includere le dinamiche forestali di assorbimento di anidride carbonica e decomposizione naturale della biomassa legnosa nell'LCA.

La ricerca è condotta per mezzo di due casi studio: il primo è costituito dall'LCA della legna da ardere nel Nord-Est Italia; il secondo riguarda la produzione di cippato nell'area del Pacific Northwest negli Stati Uniti. La tesi è costituita da otto capitoli. Nel Capitolo 1 si descrivono il quadro legislativo e lo stato dell'arte delle esperienze internazionali e dei progetti di ricerca sull'argomento. Viene inoltre effettuata una review di studi di letteratura mettendone in luce le principali limitazioni e definendo gli obiettivi di ricerca. I Capitoli 2 e 3 analizzano la catena di fornitura dei prodotti legnosi per fini energetici, fornendo dati di riferimento per i processi di estrazione e produzione della biomassa e per le caratteristiche fisico-chimiche del legno e la metodologia LCA, in termini di standard, banche dati, software e metodologie disponibili. I Capitoli 4 e 5 presentano i risultati dei due casi studio che identificano nel trasporto la fase critica dell'LCA, nel caso della legna da ardere legato all'importazione della materia prima dall'estero, nel caso del cippato legato al trasporto su strada forestale. Il Capitolo 6 riguarda la valutazione dei carbon sinks e stocks nelle aree di studio precedentemente analizzate. Nel capitolo 7 si affronta il problema di come includere il sequestro di carbonio in foresta nell'ambito dell'LCA. Questo ha portato allo sviluppo di una metodologia per effettuare un "LCA dinamico", che, nel Capitolo 8, viene applicata ad un caso studio nel Pacific Northwest. La metodologia si base sull'utilizzo del forzante radiativo per valutare l'impatto delle diverse fonti di emissioni ed assorbimento sul cambiamento climatico. I risultati mostrano che, nel caso studio considerato, esiste un "Radiative Forcing Turning Point", ovvero un punto, situato circa a metà del periodo di rotazione della foresta (tra 17 e 21 anni), dove gli impatti del ciclo di vita vengono compensati dagli assorbimenti di anidride carbonica e oltre il quale la biomassa produce un beneficio netto in termini di bilancio del carbonio. Lo sviluppo di un LCA dinamico è molto innovativo nel quadro dell'LCA e ha permesso discutere la veridicità dell'assunto della carbon neutrality.



## Summary

The use of wood products for energy production has increased in the last years as an alternative to fossil fuels. International and national regulations have supported the use of wood for energy since it is considered to have a lower environmental impact than traditional energy sources (Cherubini et al., 2009; Lippke et al., 2011b; Sathre and Gustavsson, 2012; Sathre and O'Connor, 2010). These policies have been intensifying in the last period, setting more and more ambitious objectives for the near future. As a consequence, it is expected that this sector will considerably increase in the next years. For this reason, it is of fundamental importance to appropriately determine its environmental impacts.

The approach initially adopted by the Kyoto Protocol for the evaluation of the sustainability of bio-energy, which is still adopted in most of the environmental policies (EPA, 2011; IPCC, 2006; United Nations, 1997) is based on the assumption of carbon neutrality, which affirms that the carbon dioxide emissions generated during the biomass combustion equal the carbon dioxide sequestered from the atmosphere by the trees for their growth attributing to the energy from biomass an emission coefficient of zero (BSI, 2011; EPA, 2011; European Commission Joint Research Centre, 2010).

However, other phases of the life cycle of wood products for bio-energy can play an important role in the overall environmental impact. In fact, greenhouse gas emissions are released for the consumption of fossil fuels and materials used in the forest operations of harvesting and processing the wood in order to produce the biomass with the specific characteristics needed to be used to produce energy. Furthermore, the transportation of the harvested wood can follow different paths, depending on the morphology of the site and on the accessibility of the transportation means to the harvesting site, thus releasing greenhouse gas emissions to the atmosphere, due to the fossil fuels used in the transportation means. Moreover, if the raw materials are imported from abroad, long distances have to be travelled in order to take the wood from the harvesting site to the processing site. In addition, even though the use of wood has often been related to its benefit in terms of global warming, some other aspects should be considered in evaluating the sustainability of bio-energy, e.g. the combustion of wood can be critical for the local atmospheric pollution and the impact on human health (Cespi et al., 2014; Solli et al., 2009).

For these reasons the evaluation approach initially adopted has been progressively replaced by more global approaches which consider the whole emissions of the supply chain. The internationally recognized approach is called Life Cycle Assessment (LCA) and, based on the ISO 14040-44, is defined as the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO, 2013a, 2006a). Through the LCA it is possible to evaluate the impact on different impact categories, i.e. global warming,

ozone depletion, eutrophication, acidification, smog formation, eco-toxicity, human health criteria, human health cancer and human health non-cancer.

Even though the LCA is a powerful tool it is relatively recent and presents several limitations, which have been outlined through the analysis of the scientific literature.

First of all it has been revealed that there is heterogeneity in the application of the methodology, particularly regarding the system boundaries and the types of emissions included in the study. As long as the Italian reality is concerned, a few studies about the impacts associated with the forest operations have been found (Valente et al., 2011).

The carbon neutrality assumption is used in the majority of the LCA studies of biomass (Cherubini et al., 2009; Helin et al., 2013; Lippke et al., 2011b; McKechnie et al., 2011; McManus, 2010; Routa et al., 2012a, 2012b; Whittaker et al., 2011). This assumption is related to a specific characteristic of the LCA, i.e. its static approach. In fact in LCA all the emissions and absorptions are considered instantly released at the beginning of the evaluation period. Therefore the result is a picture of the environmental impacts at a specific point in time. This represents a strong limitation in the LCA studies, in fact the biomass growth in forest to regenerate the harvested wood can take a long time depending on the forest management adopted and factors e.g. the rotation period, the type of species, the age of the forest, the rate of harvesting. The rate of growth of biomass is related to the rate of absorption of carbon dioxide from the atmosphere through the photosynthesis which has a potential beneficial effect on global warming. Therefore, for wood products the carbon sequestration may be crucial to determine the real impact on global warming of woody biomass bio-energy. Also, the natural decomposition of wood in forest slowly releases greenhouse gases over time and can take many decades to complete.

These aspects are not normally considered in LCA. In order to quantify them the traditional LCA approach has to be extended and a dynamic approach should be used which considers the effect on global warming of carbon dioxide emissions and removals according to a specific dynamic function over time. To determine the real impact of bio-energy on global warming the impact in terms of Radiative Forcing and its cumulative effect over time should be considered.

The following objectives have been defined:

1) Perform a Life Cycle Assessment of wood products for bio-energy to evaluate their environmental impacts with the following specific targets (targets are subdivided for the specific phases of the life cycle):

a. Raw materials supply:

Evaluation of the global and local impact of the transportation associated with the importation of raw materials from abroad (long supply chain) compared to produce them locally (short supply chain).

b. Production

Evaluation of the environmental impact of the forest operations of harvesting and processing the wood.

c. Distribution

Evaluation of the contribute of transportation in function of different logistics scenarios based on the morphology of the site and the means of transportation adopted.

d. End of life:

Evaluation of the global and local impact of the wood combustion to produce bio-energy.

2) Incorporate dynamic functions of greenhouse gases release and uptake into the LCA framework to develop a “dynamic LCA” for the following aspects:

a. Carbon sequestration in forest

Evaluation of the effect of forest management, considering the following factors: type of species, disturbances, timeframe, type of management.

b. Decomposition of residues left in forest.

In Chapter 1 the legislative framework of bio-energy is described, including International, European and National legislation and policies to mitigate climate change and the incentives system for the energy produced from renewable sources. Furthermore the state of the art of the international experiences and research projects about the evaluation of the environmental performances of wood products for bio-energy are presented.

Chapter 2 describes the methodologies available for accounting the environmental impacts of bio-energy, focusing on the Life Cycle Assessment approach, which is described based on international standards. The chapter also analyzes the wood products supply chain for bio-energy. The state of the art of the LCA studies of wood product for bioenergy has been reviewed and some limitation outlined. This chapter also describes the motivation of the study, the research questions and the objectives, which will be addressed through some case studies.

Chapter 3 analyzes the results of a Life Cycle Assessment of firewood. performed in North-Eastern Italy. The focus of the study is to quantify the impact of the importation of the raw material from abroad (Balkans area) on the impact categories Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Human Health Potential (HTP) and to compare the long and the short supply chain. Also the local impact of the wood combustion has been analyzed to determine its contribution on global and local scale to the overall impact.

A sensitivity analysis has been performed to determine the critical distance of transportation for impact categories. Lastly how to offset the carbon dioxide emissions of the overall life cycle has been evaluated through forest management by saving a part of the biomass increment in forest.

Chapter 4 describes the results of a Life Cycle Assessment of wood chips performed in the U.S. Pacific Northwest. The study focuses on the impact of different types of forest operations and

logistics schemes by comparing a benchmark scenario with three alternate scenarios varying the type of logistics, i.e. type of roads and distances travelled. The study also addressed the issues of allocation and of the avoided impacts within the LCA. In this case, logs and residues are produced from the forest and the impacts are allocated between the two products based on the mass flows. Furthermore, in the Pacific Northwest, residues are generally piled and burned in forest. Their recovery to produce bio-energy thus represents an avoided impact to the system.

A comparison of the results of the two case studies – firewood and wood chips - in terms of Global Warming Potential has also been included in this chapter.

In Chapter 5 the problem of how to incorporate dynamic functions into the LCA framework has been addressed. This has led to the development of a methodology to perform a “dynamic LCA” to incorporate the dynamics of carbon sequestration and decomposition of wood into the LCA.

A new methodology has been studied and proposed which considers the Radiative Forcing of the different sources of emissions and the decay of greenhouse gases to the atmosphere.

Through this approach it has been possible to discuss the truthfulness of the carbon neutrality assumption.

The last section outlines the main findings of the research project. The environmental impacts of wood products for bio-energy were evaluated in detail. Moreover a method has been proposed, which has general validity and can be applied to every type of wood product.

The development of the dynamic LCA is very innovative in the LCA framework since neither in LCA international standards nor in international politics this aspect has been introduced yet, although it is beginning to spark the interest of the scientific community.

Given the sharp expected increase in the future in the use of biomass for the mitigation of climate change, even small variations in the results could have enormous implications at global level.

The dynamic approach developed has contributed to fix some unsolved problems in the LCA framework. In particular it can be applied to evaluate the impact of delayed emissions over time, important aspect for both the evaluation of the carbon stored in long lasting wood products and the delayed emissions for either natural decomposition or decomposition in landfill.

In conclusion it has been found that the biomass sustainability can vary according with many factors. The type of forest management adopted in the harvesting site significantly influences the impact on global warming as well as the residues quantity and the logistics. The application of this approach could allow to define parameters in the international politics in favor of the types of biomass which have the highest benefit on the global warming considering the impacts on the overall supply chain.

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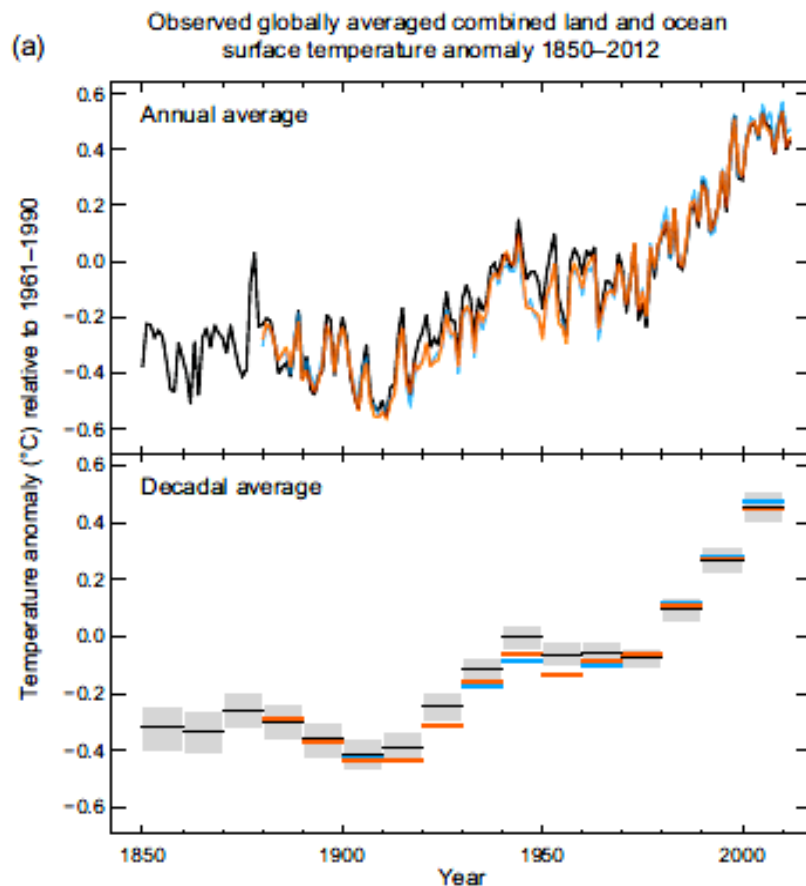
# Chapter 1

## Introduction and state of the art

### 1.1 Climate change

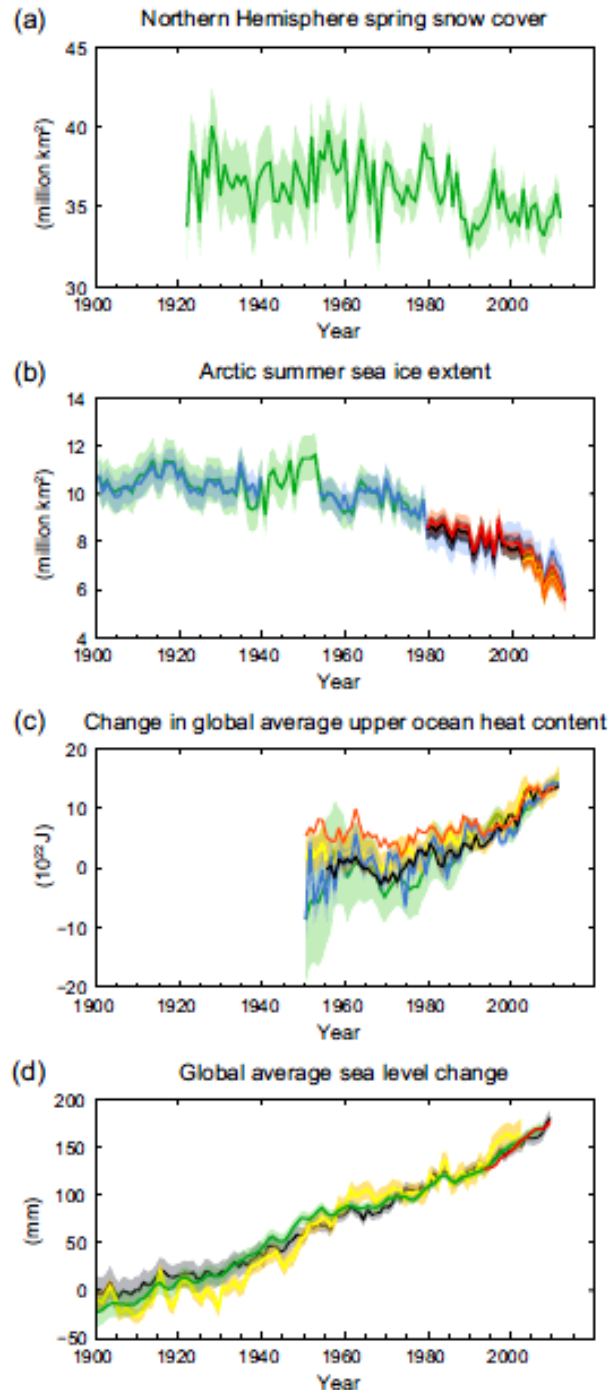
#### 1.1.1 Observations data

Climate change represents one of the major threats of this century. The global average temperature has been dramatically increasing in the last years causing average atmosphere and ocean warming. According to the 5<sup>th</sup> IPCC Report, global warming is unequivocal and since 1950s, many of the observed changes are unprecedented over decades to millennia. The globally averaged combined land and ocean surface temperature data show a warming of 0.85 [0.65 to 1.06] °C, over the period 1880 to 2012. The total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85] °C, based on the single longest dataset available (IPCC, 2013).



**Figure 1.1** Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 (IPCC 2013).

The global temperature increase is altering the equilibrium of natural ecosystem, including the water and the energy balances and the carbon cycle. The temperature increase is causing an extensive melting of glaciers and snowfields, an increase of the oceans temperature, and a global rise of sea level.



**Figure 1.2** Multiple observed indicators of a changing global climate: (a) Extent of Northern Hemisphere spring average snow cover; (b) extent of summer average sea ice; (c) change in global mean upper ocean (0–700 m) heat content aligned to 2006–2010, and relative to the mean of all datasets for 1970; (d) global mean sea level relative to 1900. (IPCC, 2013).



The IPCC updated data show that, over the period 1993 to 2009, the average rate of ice loss from glaciers around the world was  $275 \text{ Gt yr}^{-1}$ , significantly higher than the value registered over the period 1971 to 2009, which was  $226 \text{ Gt yr}^{-1}$ . The average rate of ice loss over the period 2002 to 2011 was more than six times higher than the one registered over the period 1992 to 2001 from the Greenland ice sheet and almost five times higher from the Antarctic ice sheet. The Antarctic sea ice extent increased at a rate in the range of 1.2 to 1.8% per decade.

Climate change has also been causing dramatic increase of the sea level. According to the IPCC, the rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia. The mean rate of global averaged sea level rise was  $1.7 \text{ mm yr}^{-1}$  between 1901 and 2010,  $3.2 \text{ mm yr}^{-1}$  between 1993 and 2010.

Changes in the global water cycle in response to the warming also includes increase in contrast in precipitation between wet and dry regions and between wet and dry seasons.

### ***1.1.2 The cause of climate change***

Global warming is associated with the presence in the atmosphere of certain gases, called greenhouse gases (GHG) in higher concentrations than those naturally present. GHGs, natural or anthropogenic, absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, atmosphere and clouds.

The main GHGs are:

- Carbon dioxide ( $\text{CO}_2$ )
- Methane ( $\text{CH}_4$ )
- Nitrous oxide ( $\text{N}_2\text{O}$ )
- Halocarbons (chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), perfluorocarbons)
- Sulfur hexafluoride ( $\text{SF}_6$ ).

It is unequivocal that anthropogenic increases in the well-mixed greenhouse gases have substantially enhanced the greenhouse effect (IPCC, 2013). The atmospheric concentrations of greenhouse gases have increased to levels unprecedented in at least the last 800 000 years at increasing growing rate, due to human activity, since the industrial revolution.

In 2011 the concentrations of carbon dioxide, methane and nitrous oxide were 391 ppm, 1803 ppb, and 324 ppb, and exceeded the pre-industrial levels by about 40%, 150%, and 20%, respectively (IPCC, 2013).

Global Warming is measured through the Radiative Forcing (RF), which is a measure of the change in energy fluxes caused by changes in these drivers. The total anthropogenic RF for 2011 relative to 1750 was  $2.29 [1.13 \text{ to } 3.33] \text{ W m}^{-2}$ , and it has increased more rapidly since 1970 than during prior decades. The total anthropogenic RF best estimate for 2011 is 43% higher than that reported

in AR4 for the year 2005 (IPCC, 2013).

Climate change will have inevitable economic consequences for the countries that will have to bear the costs for the actions of adaptation and mitigation and social because it will lead to a shrinking resource and worsening living conditions.

According to the latest IPCC Report, global warming is unequivocal, however, reducing the emissions of greenhouse gases in sufficient concentration to stabilize the increase in average global temperature to 2 ° C can significantly limit the damage on ecological systems, social and economic globally.

For this reason, the reduction of greenhouse gas emissions is considered an environmental priority and is the main focus of political and institutional debates. Many actions have been undertaken at different levels to mitigate climate change by imposing obligations to reduce emissions globally.

## **1.2 The International policy to mitigate climate change**

### ***1.2.1 The Kyoto Protocol***

The environmental problem began to be discussed at international level in the '80s. In 1980 the World Meteorological Organization (WMO) organized the First International Conference for the climate, during which concern was expressed about the energetic balance of the earth and its possible consequences on the atmosphere and on the climate. In 1987 the concept of sustainable development was first defined in the Brundtland Report as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987).

In order to collect and disseminate information about global warming and its risks in 1988 the World Meteorological Organization (WMO) and the United Nations Environmental Program (UNEP) instituted the Intergovernmental Panel on Climate Change (IPCC). Every five years the IPCC produces a Report with updated data about the physical basis of climate change, the mitigation strategies and the adaptation actions to adopt.

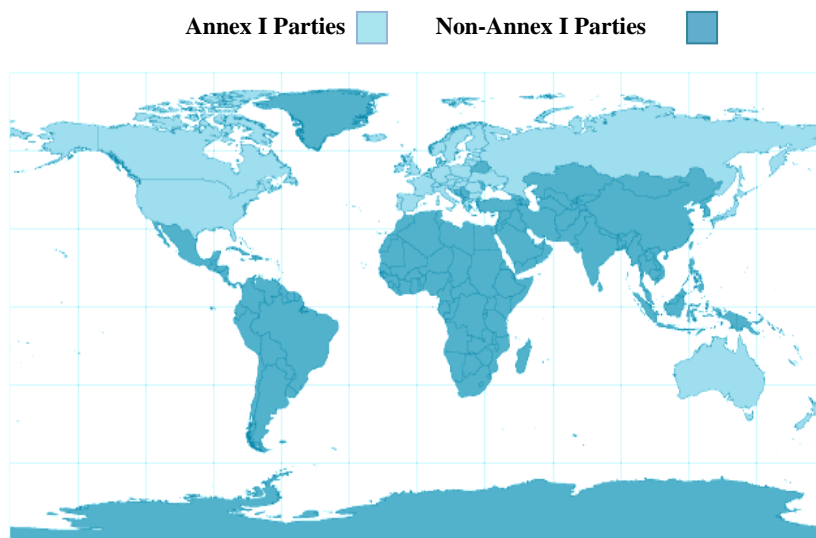
A fundamental step in the international legislation about climate change was signed by the United Nations Conference on Environment and Development in Rio de Janeiro in 1992 (United Nations, 1992a) during which the United Nations Framework Convention on Climate Change (UNFCCC) was instituted, an international environmental agreement entered into force in 1994 (United Nations, 1992b). Since then the Convention parties have been meeting once every year in a "Conference of Parties" (COP) to discuss about the climate change and mitigation strategies.

During the COP3, in 1997 in Kyoto, the first international agreement about climate change, the Kyoto Protocol, was signed, (United Nations, 1997). The Kyoto Protocol is an executive act which contains reduction objectives and targets to reduce the greenhouse gas emissions by 5.2%

compared to the 1990 values by the commitment period 2008-2012 based on the historical emissions levels of each country. The UNFCCC divides countries in two groups:

- “Annex I” parties: industrialized countries considered historically responsible of the GHG emissions, thus subject to reduction objectives, as opposed to “Non-Annex I” parties, constituted by developing countries not subject to reduction objectives.
- “Annex II” parties: industrialized countries required to financially support mitigation and adaptation to climate change in developing countries.

Thus specific reduction objectives were set for the Annex I parties as follow: European Union: -8%, United States -7%, Japan -6%, Russia, Ukraine, New Zealand 0%, Norway +1%, Australia +8%, Island +10%. The Kyoto Protocol entered into force in 2005, after the ratification of Russia and ended in 2012 at the end of the commitment period 2008-2012.



**Figure 1.3** Representation of the world ripartition between Annex I and non-Annex I Parties

Close to the end of the Kyoto Protocol commitment period, the international committee started to discuss the need of negotiating a new global agreement for the period after Kyoto. As described in the next paragraph, the international political and economical situation is now completely changed compared to the time when the Kyoto Protocol was signed, since developing country emissions surpassed those of industrialized countries, and have kept rising very rapidly.

### ***1.2.2 Current ripartition of greenhouse gas emissions by country***

In 2011, nearly two-thirds of global emissions originated from just ten countries, with the shares of China (25.4%) and the United States (16.9%) far surpassing those of all others. Combined, these two countries alone produced 13.2 GtCO<sub>2</sub> (IEA, 2013). The top-10 emitting countries are shown in Figure 1.4

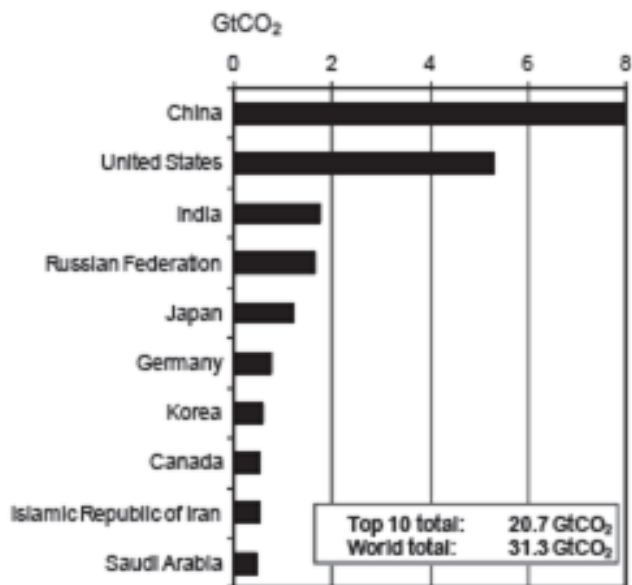


Figure 1.4 Top 10 emitting countries in 2011 (IEA, 2013).

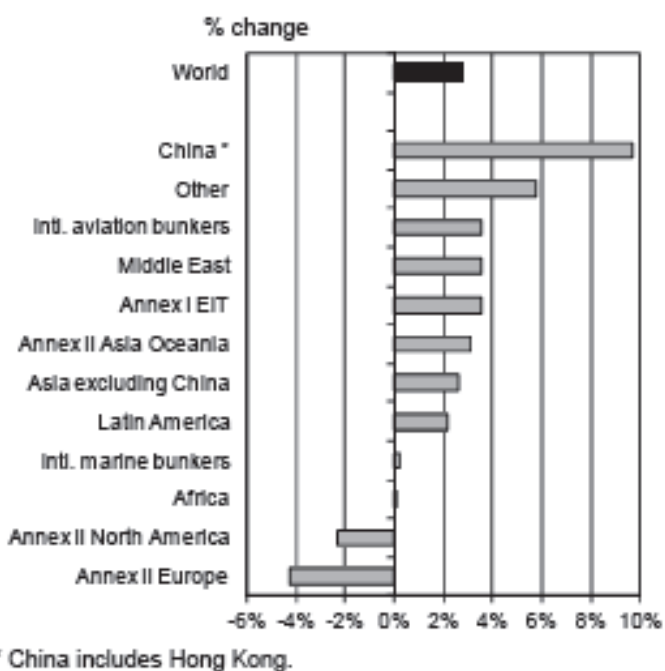


Figure 1.5 CO<sub>2</sub> emissions annual growth rate by region (2010-11) (IEA, 2013).

The first five emitters include, besides China and United States, India, Russian Federation and Japan. In 2011 Saudi Arabia displaced the United Kingdom from the group. Non-Annex I countries, collectively, represented 54% of the CO<sub>2</sub> emissions. As shown in Figure 1.5, however,

annual growth rates varied greatly: from 2010 to 2011 emissions in China grew strongly (9.7%), while emissions in Annex II countries decreased (-2.4% in North America and -4.3% in Europe).

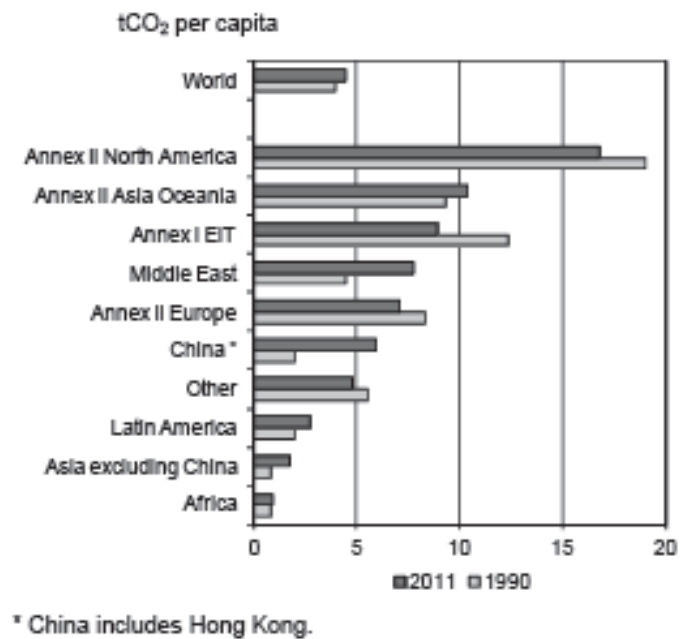


Figure 1.6 CO<sub>2</sub> emissions per capita by major world regions ( IEA, 2013).

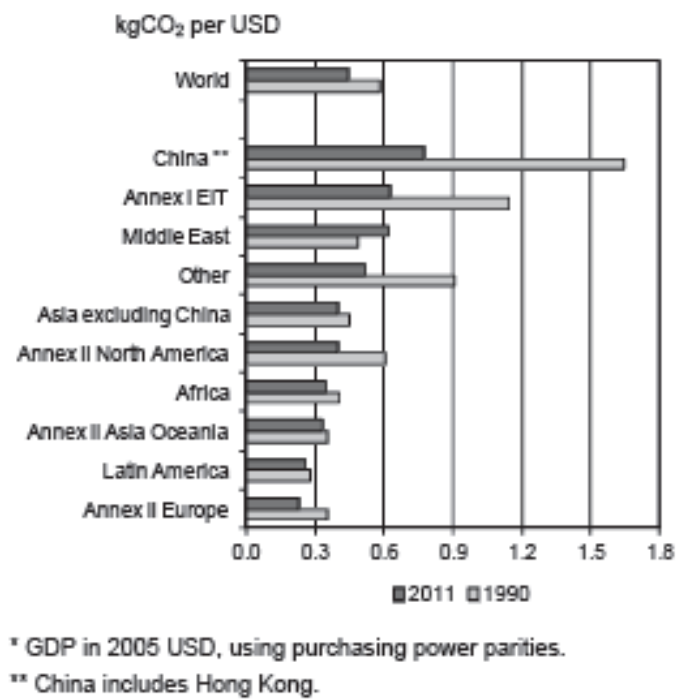


Figure 1.7 CO<sub>2</sub> emissions per GDP by major world regions ( IEA, 2013).

As different countries have largely different economic and demographical situations, these results would significantly change if considering emissions per capita or per GDP.

Other regions, like the Middle East, Annex II Asia Oceania, Asia and Latin America, experienced moderate growth (2% to 4%), while emissions in Africa remained stable. For example, among the three largest emitters, the level of per-capita emissions was 17 tCO<sub>2</sub> for the United States, 6 tCO<sub>2</sub> for China and 1 tCO<sub>2</sub> for India. On average, industrialized countries emit far larger amounts of CO<sub>2</sub> per capita than developing countries. The lowest levels worldwide were those of the Asian and African region (IEA, 2013). However, as a consequence of their rapidly expanding economies, between 1990 and 2011 China increased its per-capita emissions by three times and India doubled them. Conversely, per-capita emissions decreased significantly in both the Russian Federation (21%) and the United States (13%). Globally, per-capita emissions increased by 14%.

Emissions per unit of GDP were also very variable across regions (Figure 1.7). Although climate, economic structure and other variables can affect energy use, relatively high values of emissions per GDP, as for China and Middle East, indicate a potential for decoupling CO<sub>2</sub> emissions from economic growth.

### ***1.2.3 Towards a new international agreement post-Kyoto***

With the approval of the Bali Action Plan in 2007 the Parties supported the drafting of a new global agreement and started the negotiations for the definition of new targets to be achieved after the first commitment period of the Kyoto Protocol.

The COP15 held in 2009 in Copenhagen had the objective of signing a new international agreement with reduction targets for the post Kyoto. The European Union proposal was to reduce the greenhouse gas emissions by 20% compared to the levels of 1990 by 2020 (30% if the other countries had signed stricter objectives), the United States proposal to reduce the emissions by 17% by 2020, 42% by 2030 and 83% by 2050 compared to the emissions levels in 2005 (these targets equal respectively 4% by 2020 and 32% by 2030 compared to the emissions levels in 1990 since the emissions increased considerably from 1990 to 2005). An agreement was not reached for the failure in the negotiation between United States and emerging countries like China, India and South Africa and for the final opposition of some developing countries. At the end of the Conference of Copenhagen the developed countries agreed to create the Copenhagen Green Climate Fund to support the development of mitigation projects and policies in developing countries.

A breakthrough in the negotiation post Kyoto was the agreement at the Conference of Durban in 2011, when it was decided that the new global agreement on emissions targets will have to be achieved by 2015 to come into force by 2020. If agreement can be reached, this will be the first international climate agreement to extend mitigation obligations to all countries, both developed and developing. In the mean time the parties signed to extend the Kyoto Protocol, which would

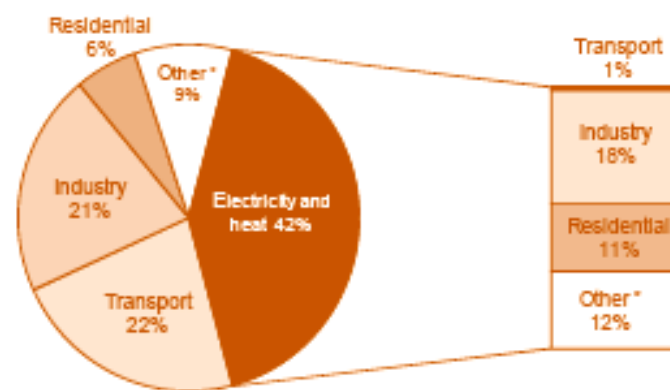
have ended at the end of 2012, for five more years, to a second commitment period, from 2013 to 2017.

A key challenge in defining the new agreement is that while obligations are to start from 2020, global emissions need to peak before 2020 if temperature rise is to be limited to below 2°C.

### 1.3 Renewable energy to mitigate climate change

#### 1.3.1 Greenhouse gas emissions and the energy sector

GHG emissions originate from most human activities, such as transportation, electricity and heat production, heating, industry, buildings and agriculture. Among human activities the largest contributor to greenhouse emissions has historically been the energy sector. Based on the International Energy Agency data, in 2011 the electricity and heat sector accounted for 42% of the total. Other contributor sectors were: transport 22%, industry 21%, residential 6% and others 9%. Electricity and heat generation, together with the transport sector produced nearly two thirds of global CO<sub>2</sub> emissions.



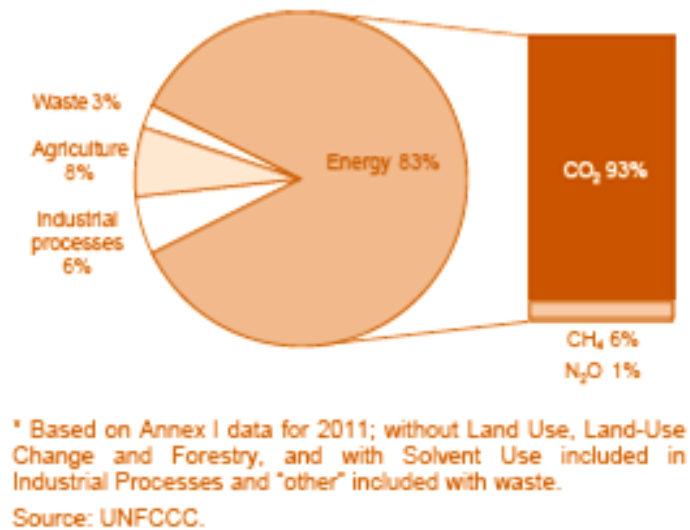
Note: Also shows allocation of electricity and heat to end-use sectors.

\* Other includes commercial/public services, agriculture/forestry, fishing, energy industries other than electricity and heat generation, and other emissions not specified elsewhere.

Figure 1.8 World CO<sub>2</sub> emissions by sector in 2011 (IEA, 2013).

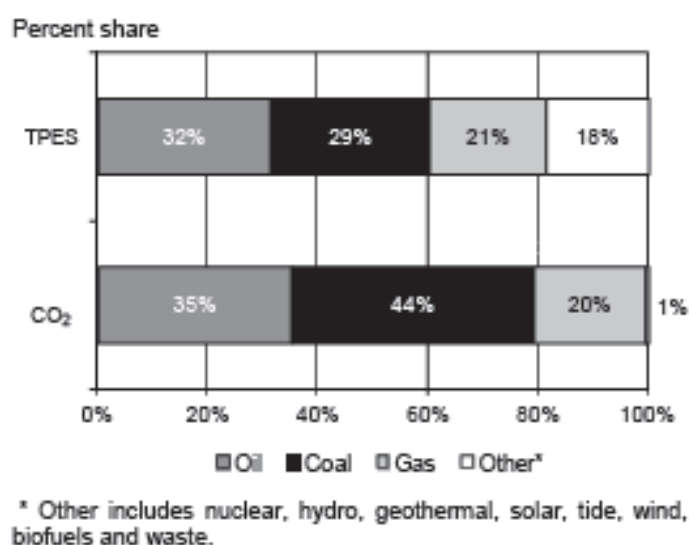
Limiting the analysis to Annex I countries, as shown in Figure, the energy use represented 83% of the anthropogenic GHG emissions. This percentage varied greatly by country, due to diverse national structures. Smaller shares corresponded to agriculture, producing mainly CH<sub>4</sub> and N<sub>2</sub>O from domestic livestock and rice cultivation, and to industrial processes not related to energy, producing mainly fluorinated gases and N<sub>2</sub>O (IEA, 2013).

Generation of electricity and heat are the main cause of greenhouse gas emissions because worldwide they are heavily relying on fossil fuels.



**Figure 1.9** Shares of anthropogenic GHG emissions in Annex I countries, 2011 ( IEA, 2013).

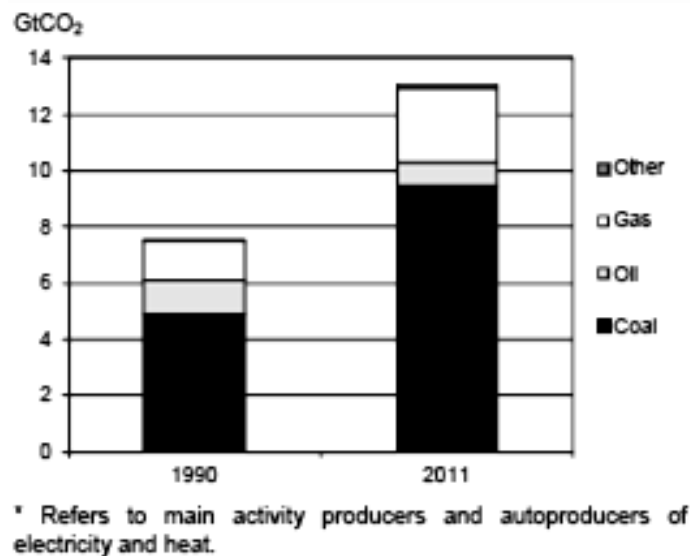
As shown in Figure 1.10 in 2011, fossil sources accounted for 82% of the global total primary energy supply, oil providing 32% of the world primary energy supply, coal 29%, gas 21% and other sources, including nuclear, hydro, geothermal solar , tide, wind, biofuels and waste, 18%. Although coal represented 29% of the world energy supply, it accounted for 44% of the global CO<sub>2</sub> emissions due to its heavy carbon content per unit of energy released. As compared to gas, coal is nearly twice as emission intensive on average (IEA, 2013). Renewable resources contribute was only 1% of the whole CO<sub>2</sub> emissions, since they are considered carbon neutral.



**Figure 1.10** World primary energy supply and CO<sub>2</sub> emissions: shares by fuel in 2011 (IEA, 2013).



As shown in Figure 1.11 the use of coal is responsible of the large majority of CO<sub>2</sub> emissions from electricity and heat generation.



**Figure 1.11** CO<sub>2</sub> emissions from electricity and heat generation (IEA, 2013).

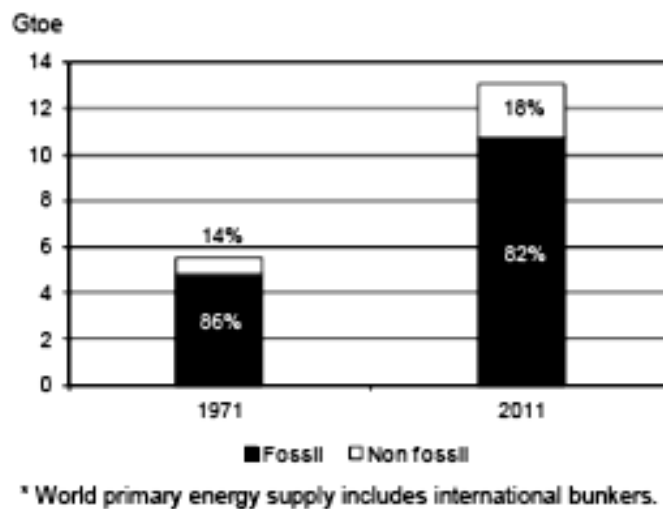
In some countries, e.g. Australia, China, India, Poland and South Africa over two-thirds of their electricity and heat is produced through the combustion of coal. Between 2010 and 2011, CO<sub>2</sub> emissions from electricity and heat increased by 4.4%, faster than total emissions and CO<sub>2</sub> emissions from the combustion of coal increased by 4.9% to 13.7 GtCO<sub>2</sub>. Coal fills much of the growing energy demand of those developing countries (e.g. China and India) where energy-intensive industrial production is growing rapidly and large coal reserves exist with limited reserves of other energy sources (IEA, 2013).

The situation is worsened by the projections of the world energy demand. With the current energy policies, the market energy consumption is estimated to increase by 44% from 2006 (497 EJ) to 2030 (715 EJ). The world energy demand expected increase is due to worldwide economic growth and development. Consequently, CO<sub>2</sub> emissions are projected to rise from 29 billion tons in 2006 to 33.1 billion tons in 2015 and 40.4 billion tons in 2030 (corresponding to an increase of 39%) (IEO, 2009).

The WEO 2013 projections are even worse, stating that by 2035 electricity demand will be almost 70% higher than current demand, driven by rapid growth in population and income in developing countries.

This growth will cause a progressive depletion of fossil resources and make the availability of conventional oil and natural gas geographically restricted (Bentley et al., 2007; Hanlon and McCartney, 2008).

Furthermore the world energy demand is expected to increase based on the growth trends that have been registered until now. Between 1971 and 2011, global total primary energy supply more than doubled (IEA, 2013).



**Figure 1.12** World primary energy supply (IEA, 2013).

The increased energy supply mainly relied on fossil fuels. Thus, despite the growth of non-fossil energy (e.g. nuclear and hydropower), considered as non-emitting, the share of fossil fuels within the world energy supply is relatively unchanged over the past 40 years. In 2011, fossil sources accounted for 82% of the global total primary energy supply, versus 86% in 1971.

### ***1.3.2 The promotion of renewable energy and energy efficiency***

The Kyoto Protocol contains information about how to reduce the greenhouse gas emissions suggesting mitigation actions. Among these the role of the energy sector is crucial. The energy consumption in fact is the first cause of greenhouse gas emissions at global level. Thus the mitigation actions are mainly focused on the reduction of energy consumption, increase of the energy efficiency, use of renewable resources and sustainable use of agriculture. In order to achieve the objectives of the Kyoto Protocol in 2000 the European Union developed the First European Climate Change Program (ECCP) which identifies a list of priorities and politics to reduce the greenhouse gas emissions. The actions included the first proposal of a Directive to promote the use of bio-fuels to produce electricity and heat (combined heat and power bio-fuels). Other measures included the agricultural and forest sector, particularly the management of forest and agricultural soils.

The Kyoto Protocol was ratified by the European Union through Decision 2002/358/CE (European Council, 2002). In particular, the flexible mechanisms proposed by the Kyoto Protocol were accepted and developed by the European Union. Through the Directive 2003/87/CE the European

Union Greenhouse Gas Emissions Trading Scheme was established (European Parliament and Council, 2003a). The Directive requires that, from January 1<sup>st</sup> 2005 all the energy producers and the main GHG emitters, obtain an authorization to emit. The authorization is based on National Plans elaborated by each country to determine the total amount of emission units for each plant. At the end of the year, those companies that have saved emissions units can sell them in the market to companies which have emitted more than what was assigned to them.

In 2005 the Second European Climate Change Program was approved, revising and improving the strategies included in the ECCP I. Through the COM(2008)30 the European Union approved the 2020 Energy and Climate package, which combines the energetic politic with the ambitious target of greenhouse gas emissions reduction (European Commission, 2008). The European Commission has pointed out the importance of the contribution of biomass to reach their goals on climate and energy in 2020. Through the Energy and Climate package, the European Union adopted new instruments to achieve the following goals by 2020:

- 20% greenhouse gas emissions reduction compared to the 1990 levels (30% if other industrialized countries will comparably commit and sign an agreement post-Kyoto);
- 20% energy consumption reduction through the improvement of the energy efficiency;
- 20% increase in the production of electricity from renewable sources.

In detail, the package involved the following steps:

- emissions reduction targets for the Member States of the European Union 2020: Decision 406/2009/EC (European Parliament and Council, 2009a);
- new common framework for the promotion of renewable energies: Directive 2009/28/EC ;
- revision of the system of emissions trading for greenhouse gases (ETS) for the post-2012: Directive 2009/29/EC (European Parliament and Council, 2009b);
- reduction of greenhouse gas emissions in the life cycle of fuels: Directive 2009/30/EC.

The EU Roadmap for a Low Carbon Economy sets a GHG emissions reduction goal of 80% by 2050. The key points of the European Union energy policy are:

- energy saving;
- increased energy production from renewable sources;
- liberalization of the market, eliminating geographical monopolies and giving the possibility to buyers to choose their supplier;
- integration of GHG reduction targets in the energy policy;
- reduction of the environmental impacts in the energy supply chains;
- security of energy supply;
- low cost of the energy.

The Directive 2009/28/EC on the promotion of renewable energy requires EU member states to adopt National Action Plans for renewable energy, containing national targets for the share of

energy from renewable sources consumed in transportation, electricity and heating/cooling in 2020 to ensure that, by that time, an average of 20% of the EU energy consumption comes from renewable sources (European Parliament and Council, 2009c). Furthermore the Directive sets an additional national target for the transportation sector, providing that the energy share from renewable sources in all the forms of transportation will be in 2020 at least 10% of its total national energy consumption.

The Directive 2009/30/EC on the reduction of greenhouse gas emissions in the life cycle of fuels sets technical specifications for bio-fuels. Under the directive, the greenhouse gas emissions produced by the fuel cycle must be reduced by at least 6% by 2020 (European Parliament and Council, 2009d). The goal, set by the Directive, will be ensured by the prohibition to sale petrol and diesel fuels with sulfur and additives content higher than the new limits established by the Directive and the new features that bio-fuels will have to respect. For the production of bio-fuels, in fact, the use of raw materials that could cause damage to the agriculture and the land use change which could lead to an irreversible loss of carbon will be prohibited. The Directive applies to road vehicles, non-road mobile machinery (including inland waterway vessels when not on the sea), agricultural and forestry tractors and recreational craft.

The Directives 2003/54/EC and 2003/55/EC aim at opening the electricity and the gas market respectively, creating the conditions for effective competition and for the creation of a market which sets the standards for the production, transport and distribution, licensing, and networks operation (European Parliament and Council, 2003b, 2003c).

Similarly to the European Union, in 2007 the United States approved a system of economic incentives to bio-fuels. The Energy Independence and Security Act aims to gradually replace the use of fossil fuels with biofuels. In order to be eligible for public procurement, it is required that the overall greenhouse gas emissions of cellulosic bio-fuel produce 60% lower carbon emissions relative to jet fuel produced from fossil fuel (U.S. Government, 2007).

At national level, Italy has been implementing a series of politics to reduce greenhouse gas emissions in compliance to international and European legislation. Through the Law n.120 of June 1<sup>st</sup>, 2002 Italy ratified the Kyoto Protocol, according to whom it is committed to reduce greenhouse gas emissions by its national reduction target of 6.5% compared to the 1990 levels (Parlamento Italiano, 2002). With CIPE "Resolution of 19/12/2002, Italy adopted a National Plan for the Emissions Reduction (CIPE, 2002). The mitigation actions in accordance with the Kyoto Protocol include the improvement of the energy efficiency and use of renewable energy in relevant sectors of the national economy, the protection and improvement of carbon sinks and stocks, promotion of sustainable forest management practices, afforestation and reforestation the promotion of advanced and innovative green technologies and the adoption of fiscal incentives to reduce GHG emissions.

The Directive 2003/87/EC has been transposed into national law through the Legislative Decree 216/2006. The decree identifies the procedure which leads to the approval of the National Allocation Plan for renewable energy in Italy (NAP) and establishes the emissions and the emission shares National Registry.

The Legislative Decree 28/2011 implemented the Directive 2009/28/EC on the promotion of renewable energy, which sets binding targets for each Member State, consistent with the overall objective of the EU gross final consumption of at least 20% in 2020 (Consiglio dei Ministri, 2011a). For Italy, the objective is a share of not less than 17% of final energy consumption from renewable sources. To achieve the goal the decree improves the incentives system for the production of energy from renewable sources (electricity, thermal energy, bio-fuels) and for the increase of energy efficiency.

The Directive 2009/30/EC was implemented by Legislative Decree No. 55/2011 on the reduction of greenhouse gas emissions in the life cycle of the bio-fuels. The Decree defines the criteria for the environmental sustainability of bio-fuels (and bio-liquids) necessary in order to make them countable for achieving the national targets on renewable energy (Consiglio dei Ministri, 2011b).

### ***1.3.3 Incentives systems to the bio-energy production***

#### **1.3.3.1 The White Certificates or Energy Efficiency Certificates**

To promote renewable energy production and energy saving, the EU energy policy includes incentive systems to the, through the White and Green Certificates systems.

White Certificates are generated from energy saving measures evaluated based on a mandatory obligation. Subjects who saved more than the obligation target could sell those energy saves as “white certificates” to some other subjects to meet their energy saving goals.

In Italy the incentives system is managed by the Electrical Service Manager (GSE) and the Energy Market Manager (GME). The GSE role is to promote the development of renewable energy through the green and white certificates. The GME is responsible for the organization and management of the green and white certificates, the emission allowances and the energy market power exchange (IPEX Italian Power Exchange).

The Authority for the Electricity and Gas establishes the requirements for the major electricity and natural gas distributors to obtained certified energy savings. Energy Efficiency Certificates corresponding to the certified savings are issued by the Energy Market Manager to the project implementing body measured in terms of TEEs, which corresponds to 1 tep (ton of equivalent petrol) of saved energy and is valid for five years.

Subjects may decide to carry out energy efficiency actions or to buy white certificates. The price is set by the market and 1 toe corresponds to around 11628 kWh of fuels, 5347.59 kWh of electricity consumption. Certificates are of three types:

- Type I: reduction of final consumption of electricity;
- Type II: reduction of natural gas consumption;
- Type III: interventions other than the two above.

Types of interventions that are eligible to acquire TEE (they can be aggregated into a single project):

- photovoltaic plant with power <20 kWp;
- double glazing;
- high-efficiency gas boiler;
- district heating and domestic hot water production;
- small cogeneration systems for winter heating, summer cooling and hot water production;
- recovery of electricity from natural gas decompression;
- break jet taps;
- replacing light bulbs with energy saving bulbs;
- replacement of electric water heaters with natural gas water heater with sealed chamber.

Eligible entities to obtain TEEs include:

- electricity and natural gas distributors;
- companies controlled by the distributors;
- companies operating in the energy services (ESCO);
- subjects with mandatory energy manager.

ESCOs are companies which finance, develop, install projects to improve energy efficiency so that the saved energy is worth enough to repay the cost of investment.

The customer does not pay at the time of construction, costs are covered by the ESCO which obtains loan at favorable interest rates. The nature of the contract between the ESCO and the customer is associative: the customer receives free energy for e.g. 20 years, leaving the incentives of the energy bill to the ESCO; the customer becomes owner of the system after 20 years while the initial risk of the project is entirely assumed by the ESCO.

#### 1.3.3.2 The Green Certificates

Green Certificates are generated from increasing the share of energy produced from renewable sources compared to a mandatory obligation. Subjects who produced a larger share of energy from renewable sources than the mandatory target, could sell the corresponding “green certificates” in the energy market.

In Italy in 1999 the Bersani Decree replaced the CIP 6 system with the Green Certificates (Consiglio dei Ministri, 1999). The eligible plants included:

- plants powered by renewable sources, including hybrids, entered into operation after April 1<sup>st</sup> 1999 as a result of new construction, expansion, renovation of all or part of them;
- co-combustion plants (hybrid plants);
- cogeneration plants combined with district heating which satisfy the conditions foreseen in the Ministerial Decree 18/12/2008 (Ministero dello Sviluppo Economico, 2008).

The requirement for electricity producers from fossil fuels was to produce a percentage of electricity from renewable sources: they can either do it independently or buy green certificates.

A green certificate corresponded to 1 MWh produced from renewable sources. The value of green certificates was added to the fare of the energy sold in the network, which varied depending on certain energy intervals. The green certificates thus doubled the value of a system which used renewable sources compared to a traditional one which uses fossil fuels.

The period entitled to receive green certificates:

- 15 years for plants using renewable sources and for thermal power plants entered into operation before April 1<sup>st</sup>, 1999 and that, after December 31<sup>st</sup>, 2007, began to operate as hybrid power plants;
- 12 years for plants using renewable sources entered into operation before December 31<sup>st</sup>, 2007, and for thermal power plants which entered into operation began operating before April 1<sup>st</sup>, 1999, which began to function as a hybrid plants before December 31<sup>st</sup>, 2007
- 8 years for non-incentivized electricity from renewable sources in cogeneration plants combined with district heating and also hybrid-powered plants from non-biodegradable waste that entered into operation by December 31<sup>st</sup>, 2006.

### 1.3.3.3 All-inclusive fare

In case of small renewable energy plants an all-inclusive fare is used as a form of incentive for each kWh produced and for each kWh sold.

On request of the manufacturer, for plants entered into operation after December 31<sup>st</sup>, 2007, with average nominal annual power not exceeding 1 MW and 0.2 MW for wind plants, the net energy can be incentivized, in alternative to the green certificates, through an all-inclusive fare, variable depending on the source, for a period of 15 years.

Eligible plants include:

- wind plants for power <0.2 MW;
- geothermal;
- wave;

- hydraulic plant different from the previous one;
- biogas and biomass;
- landfill gas, from sewage treatment plant and liquid bio-fuels.

The all inclusive fare can change every 3 years. Only one transition from green certificates to fixed rate or vice versa is possible.

The Romani Decree n.28 of 2011 introduced large modifications in the incentives system for plants commissioned after December 31<sup>st</sup> 2012 which include:

- linear reduction of the mandatory portion that will cancel in 2015;
- the import will not be subject to obligation since 2012;
- expected cut the value of the green certificates that affects retroactively existing installations;
- the all-inclusive tariffs will remain fixed for the duration of the incentive.

Specific incentives for:

- bio-methane used in high yield (80%) cogeneration plants for the electricity production;
- biogas biomass, bio-liquids installations, into operation after December 31<sup>st</sup>, 2012, combined with other government incentives in the case of cogeneration plants and regenerative powered by solar or biomass or biogas.

#### **1.4 The use of wood for bio-energy**

As described above, the use of bio-energy is considered to be crucial to fight climate change. The energy sector, in fact, is the dominant contributor to global warming because of the current large use of fossil fuels for energy production which is responsible of the release of big quantities of greenhouse gas emissions to the atmosphere.

To reduce greenhouse gas emissions legislation and incentives systems have been introduced to promote and diffuse the use of renewable energy. Worldwide bioenergy provides today only 10% of the world's total primary energy supply and most of this is used in the residential sector for heating and cooking purposes (GBEP, 2007).

Among different ways of producing renewable energy, biomass is largely used. The term "biomass" refers to organic matter that has stored energy through the process of photosynthesis. The chemical material (organic compounds of carbons) are stored and can then be used to generate energy. Common examples of biomass include food crops, crops for energy (e.g., switchgrass or prairie perennials), crop residues (e.g., corn stover), wood waste and byproducts (both mill residues and traditionally noncommercial biomass in the woods), and animal manure (Bracmort and Gorte, 2009). Among those wood represents one of the most promising biomass source. Wood has been the first fuel historically adopted before being replaced by fossil fuels. In developing countries



traditional bioenergy use (fuelwood and charcoal) still dominates since up to 95% of national energy consumption relies on biomass (Cherubini et al., 2009).

Wood is largely available worldwide and, if correctly managed through a sustainable management, can represent an unlimited source.



**Figure 1.13** Representation of the carbon cycle.

As shown in Figure 1.13 wood, as renewable resource, is part of the natural carbon cycle. Carbon is converted and stored in woody biomass through photosynthesis. Humans interfere with the natural carbon cycle by harvesting, processing, transporting and using the wood material. When wood is harvested carbon is transferred from one carbon pool (standing forest) to another (harvested wood product). Harvested wood can have different destinations: it can be used either to produce bio-energy or long lasting products or products for the paper industry.

When burned to produce bio-energy the carbon content is released back to the atmosphere during combustion. Forest operations of cutting, chipping and transporting wood as well as the manufacture of wood products release greenhouse gas emissions which depend on the technology adopted.

## 1.5 The environmental sustainability of woody biomass bio-energy

### 1.5.1 Life Cycle Assessment (LCA)

The use of woody biomass for energy production is part of the strategy to reduce the global greenhouse gas emissions. Since wood is one of the oldest fuel used for energy production, several

methodologies have been developed during the years to evaluate its sustainability. Some of them have been abandoned, most of them still coexist.

Biomass energy is often considered for its potential of mitigate climate change, so global warming is the focal indicator for bio-energy considerations. However more recent methods consider the sustainability from a wider point of view, expanding the system boundaries to the whole life cycle of the product and considering a larger set of impact categories.

An overview of the evaluation methodologies is presented, adopted both in international politics and on voluntary level. They can be classified in two main approaches:

- I approach limited to direct emissions;
- II approach: life cycle approach.

The first approach started in the '80s and is still present in most of the regulations for the mitigation of climate change. It consists in evaluating the environmental impacts of biomass, based on the direct emissions released in atmosphere by its combustion, assumed to be equal to carbon absorption in forest. This method is used in the Kyoto Protocol and described in the IPCC Guidelines (IPCC, 2006) which include specific evaluation methods for each activity sector. In this approach different stages of the biomass life cycle are accounted separately.

In the Kyoto Protocol the forestry sector is accounted through art.3.3 (afforestation, reforestation and deforestation) and art.3.4 (forest management). Through the carbon stock method the increase in biomass growth in forest is accounted as a negative emissions and reported in the National Inventories for the GHGs to offset the emissions.

The harvesting activity on the contrary is assumed to be an instantly release of carbon dioxide to the atmosphere based on the default assumption that all the carbon dioxide stored in the wood in forest is instantly emitted into the atmosphere after harvesting. This assumption is like considering that all the harvested wood is instantly burned.

For the first commitment period of the Kyoto Protocol (2008-2012) no distinction was made between wood products for bioenergy and long lasting wood products, since the harvesting activity was accounted as an instant carbon dioxide emission, not considering that the carbon could be stored in long lasting wood products for decades as carbon stock.

However the 2006 IPCC for Harvested Wood Products recognized the role of carbon stocks in wood products and its methodological framework and their introduction in the emissions accounting has been much discussed in the negotiations for the post-Kyoto. They have been recently introduced in the accounting for the GHG Inventories for the Kyoto Protocol after the conference of parties in Durban. Based on the IPCC Guidelines, the energy produced from woody biomass is consider to have an emission factor equal to zero. This statement is based on the assumption that all the carbon stored in biomass is instantly released during combustion as carbon

dioxide and that the carbon dioxide released equals the carbon dioxide that was absorbed from the atmosphere for the biomass growth.

Given the importance of the Kyoto Protocol at international level, most of the subsequent international legislations for the mitigation of climate change adopted the same approach.

Also on voluntary level, many standards for the evaluation of the environmental sustainability of woody biomass bioenergy are based on this assumption.

The second approach is called “life cycle assessment” (LCA). This approach is relatively recent, since it began to be adopted as voluntary tool at the beginning of 2000. Life cycle assessment is defined as the “Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”. It is a global approach which aims to evaluate the overall impact of a product from the acquisition of the raw materials from the environment, until the end of life, considering all the phases of transportation, forest operations and wood processing needed to manufacture the final product and distribution of the product to the end users. The LCA approach recognizes the importance of expanding the system boundaries going beyond the calculation to the whole supply chain to identify the most critical stages and define a real reduction strategy acting where it is more effective and economically viable.

The LCA calculation can be performed according to one of the following approaches:

- From cradle to grave: it takes into account the environmental impacts throughout the entire life cycle from the acquisition of the raw materials and natural resources from the environment to the production phase, the distribution phase until the final disposal;
- From cradle-to-gate: it takes into account the environmental impacts from the acquisition of the raw materials from the environment until the product manufacture, including all the upstream emissions.
- From gate-to-gate: it takes into account the environmental impacts for the product manufacture.

LCA is constituted by the following four phases:

- Goal and scope definition
- Life cycle inventory analysis (LCI)
- Life cycle impact assessment (LCIA)
- Life cycle interpretation.

In the LCA framework, the evaluation of the greenhouse gas emissions with life cycle approach is called Carbon Footprint. LCA does not limit the evaluation to global warming, but it includes many other impact categories on both local and global scale, for air, water and soil compartments, e.g. stratospheric ozone depletion, human toxicity, acidification, eutrophication, eco-toxicity, photochemical ozone creation potential (POCP), land use, depletion of abiotic resources, habitat and ecosystems. However, as discussed above, the impact on global warming is a key indicator to

evaluate the bioenergy sustainability. The LCA methodology will be described in detail in Chapter 3 of this dissertation.

#### 1.5.1.1 International LCA programs and standards

Life Cycle Assessment is performed based on internationally recognized approaches. The international standards for Life Cycle Assessment are ISO 14040 and ISO 14044. In 2013 the ISO published ISO 14067, a specific standard for the quantification and reporting of the carbon footprint of products (ISO, 2013a).

For the evaluation of the emissions at organization level currently the most common international standard is the ISO 14064 (ISO, 2006c). This standard specifies requirements for measuring, monitoring, reporting and verifying the greenhouse gas emissions and removals within the organization system boundaries, establishing that the accounting is mandatory for the emissions of the first two categories (direct and indirect from energy consumption) and optional for the third category (other indirect). In 2013 the ISO published the ISO 14069, which represents a guideline for the application of ISO 14064 (ISO, 2013b). Another widely used standard for the calculation of the greenhouse gas emissions at organization level is the GHG Protocol, developed the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). This approach provides a detailed guide, freely accessible online for the compilation and reporting of the emissions of organization. The wide adoption of this standard is attributable to the inclusion of many stakeholders in its development.

In 2011 the GHG Protocol published a specific document on the Corporate scope 3 (value chain) accounting and reporting (WRI and WBCSD, 2013), which contains information on how to calculate the indirect emissions of the organization to understand, manage and report the GHG emissions throughout the supply chain.

In line with the ISO standards the European Commission Joint Research Centre, within the European Platform on Life Cycle Assessment (EPLCA), developed the ILCD handbook, consisting of a set of documents including a general guide for LCA and a specific guide for LCI data sets builds on the general guide, which provides more detail for the generation of specific types of data (European Commission, 2010). Specific technical documents have been developed for the Carbon Footprint, both at product and at organization levels.

In the last years, several programs have been developed at international level for the calculation and management of the environmental performances of products at voluntary level.

Since 2001, the United Kingdom has implemented a program with the Carbon Trust to calculate, reduce and report the greenhouse gas emissions, contributing to provide technical expertise for the development of one the most spread international standard, the PAS 2050. The PAS 2050 (BSI,

2011), developed by Carbon Trust, Defra and the British Standards Institute (BSI), includes specific requirements regarding the definition of the objectives, the inventory analysis, the identification of the system boundaries and the temporal aspects of the GHG emissions, clarifying the approach that should be considered by the organizations that implement the Carbon Footprint and simplifying procedures of LCA focusing on the emissions of greenhouse gases. The PAS, while basing its roots on the methodology of Life Cycle Assessment, clarifies important issues providing a rigorous and practical approach for the carbon footprint. In Germany from 2007 to 2009 the PCF Project was carried out to promote the emissions reduction along the supply chain. Furthermore Germany developed a label system called Blue Angel, which applies to goods and services that have, based on a life cycle approach, less impact than the market average.

One of the most ambitious program was undertaken by France in 2009, through the Grenelle Law, which launched a project for the quantification of the environmental impacts and the communication of the results to the end users. The goal was to test different aspects e.g. evaluation methods, data sources, communication methods, consumers response, cost, impact on business. At the same time the Ademe-Afnor platform developed a general methodology to calculate the environmental impacts of products to produce Product Category Rules and to build a public database for the life cycle of products. The law aimed to make mandatory the diffusion of the information about significant environmental aspects, such as the greenhouse gas emissions, water and resources consumption, impact on biodiversity, through environmental labels applied on products. Thus the consumer will be able to compare and choose the products to buy, also based on sustainability criteria.

Programs for the calculation and reporting of the carbon footprint of the products have also been growing in Sweden, with the International EPD system and the Climate Certification of food chain, a Swedish initiative to assess the impact on climate change in the food sector developed from the EPD label (ISO, 2006d), in Switzerland with the Climatop labeling, Intelligent Labelling, Climate Friendly Products and in Austria with the Zurück zum Ursprung labeling system.

Also in Asia programs for the calculation and labeling of the carbon footprint are becoming more common: in Korea, after a 9-month pilot program, in February 2009 the Environmental Technology Institute of Korea (KEITI) introduced the Carbon Footprint Label. Since then, more than 400 products and services have been labeled. In Japan, the Ministry of Economy, Trade and Industry, in response to a Action Plan for a Low Carbon Society in 2009 launched a project for the Product Carbon Footprint (CFP) based on the ISO 14040- 44 and ISO 14025. The pilot project took three years and produced important results in terms of number of tested products, database produced and educational events organized. At the end of the pilot project the Japanese Association for the Environmental Management for the Industry (JEMAI) launched a program in April 2012 for the CFP Communication, which was be carried out based on the results obtained in the previous

three years. The goal was to give visibility to the CFP, to reduce the cost and to include a greater number of stakeholders.

Also Taiwan, Thailand and Nigeria have developed systems for the calculation and labeling of the product Carbon Footprint, respectively the Taiwan Carbon Footprint Labels, the Thai Carbon Footprint and Labelling Initiative and the Lagos State Carbon Footprint and Management Project and a pilot project started by the government in Quebec, the Carbon Footprint of Products Labelling Pilot Project from the Quebec Government.

Italy has also recently launched projects for the calculation of the environmental impacts in many productive sectors. In 2011, the Ministry of Environment allocated funding to perform studies on the carbon footprint by selecting companies operating in different sectors related to consumer goods, creating a working group whose goal was to develop and test methodologies for the calculation of sector carbon footprint.

## **1.6 State of the art of LCA of wood products for bioenergy**

### ***1.6.1 Research projects about the evaluation of the environmental impacts of wood products***

As far as the forestry sector is concerned, there are major initiatives in the international scene. One of these is the establishment in 1996 of the Consortium for Research on Renewable Materials Industry (CORRIM) from 15 research institutes to conduct research on the use of wood as a renewable material. CORRIM published a research plan containing twenty-two modules to develop a life cycle assessment (LCA) about the use of wood for residential and for other uses. The research plan led to the creation of a comprehensive inventory of inputs and outputs of the environmental life cycle of timber products from the forest management to the final product, including its manufacture, use, maintenance and disposal. The results of the first phase of the program are published in a summary report (CORRIM, 2001).

CORRIM is one of the largest LCA organizations in North America over the last decade it has developed research protocols in compliance with the ISO standards for the life cycle inventory (LCI) for the measurement of all inputs and outputs for each processing stage, including forest management, harvesting, transportation, woodworking, manufacturing, maintenance and use, until the final disposal, producing databases that allow to quantify the emissions from the forest to the post-consumption, evaluating the emissions from a carbon pool to another and measuring the interactions between them.

The research has highlighted the impact of the management and policies on greenhouse gas emissions on the different carbon pools for the major supply regions in the United States (Bowyer et al., 2004; Perez-Garcia et al., 2005). The studies carried out by CORRIM represent an important

source of information for the purposes of this study.

At European level, the European Confederation of Woodworking Industries (CEI-Bois), the Confederation of European Forest Owners (CEPF) and the Confederation of European Paper Industries (CEPI) have created a technology platform for the forestry sector, the Forest Technology Platform (FTP) (<http://www.forestplatform.org/>). The Forest Technology Platform is led by industry to establish and implement a roadmap for research and development for the sector, and is supported by a large group of stakeholders. The FTP has developed a Vision 2030 for the wood sector, which defines as main objective to develop research and knowledge to make the forest sector competitive and promote the use of renewable forestry resources.

The work of the FTP was performed under the Seventh Programme Framework of the European Commission (2007-2013). The technology platforms are the main 'channels' to give specific inputs to work programs and for the cooperation with the European Commission in the specific area.

The main research priorities of the Platform were included in the Platform Strategic Research Agenda (SRA), the first research program that integrates all of the major networks in Europe and industrial initiatives in the forestry sector in a geographically balanced way.

Another European research project, Eforwood, aimed to develop mechanisms for evaluating the contribution of wood to the sustainable development. The project covered the entire European forestry supply chain from the production to the consumption and recycling of materials and products. Eforwood was the first project funded by the European Commission which covers the whole European forest sector.

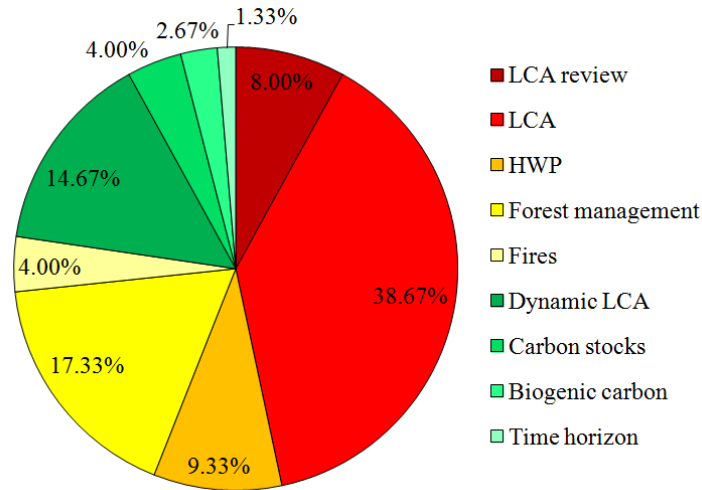
### ***1.6.2 Literary review about LCA of woody biomass bio-energy***

After analyzing the international mandatory regulations and voluntary programs framework, the scientific literature about Life Cycle Assessment of woody biomass bio-energy has been reviewed.

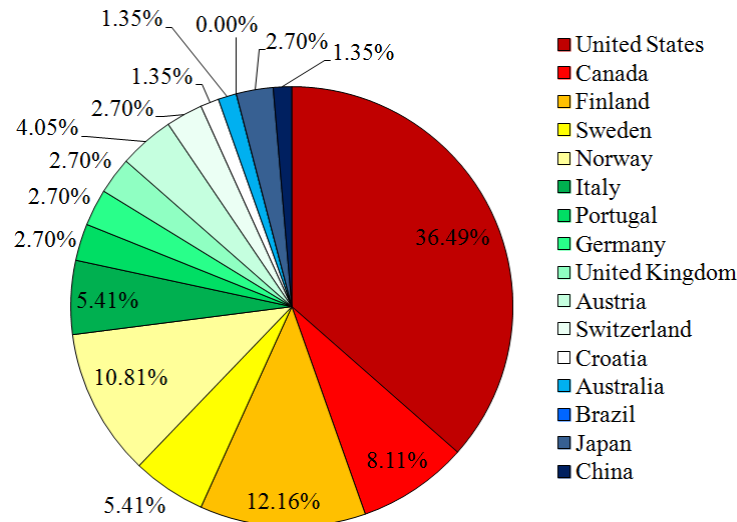
75 papers have been analyzed, 6 of them were already reviews (Cherubini, 2010; Cherubini et al., 2009; Cherubini and Strømman, 2011; Heinimann, 2012; Helin et al., 2013; Kloepffer, 2008).

Some of the analyzed papers dealt with the LCA of wood products for building constructions (Bergman and Bowe, 2010; Hubbard and Bowe, 2010; Lippke et al., 2011a, 2010; Perez-Garcia et al., 2005; Puettmann et al., 2010a, 2010b; Wilson, 2010a, 2010b, 2010c) but were still included in the review since they provided a lot of data about forest operations from the CORRIM database.

The topics addressed in the reviewed papers, the first author's organization country and the year of publication are shown in Figure 1.14 and Figure 1.15



**Figure 1.14** Ripartition of the topic addressed in the review papers.



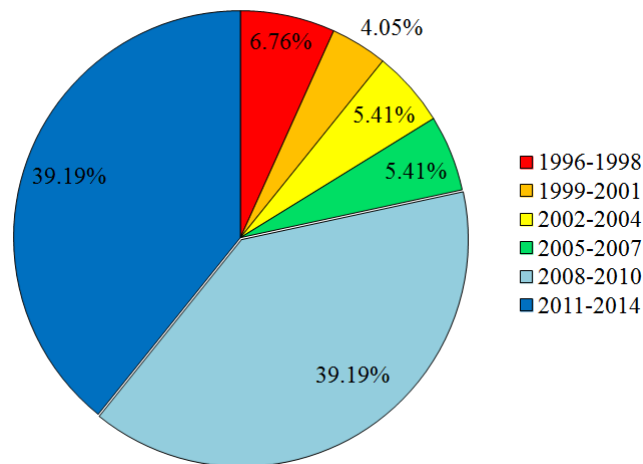
**Figure 1.15** Ripartition of the first author's organization countries of the review papers.

The majority of the review papers were LCA studies (38.67%). Papers about forest management and climate change also represented a large share of the total (17.33%) and some papers about dynamic LCAs (14.67%), harvested wood products (9.33%), reviews (8%) and others (12%) including fires management, carbon stocks, biogenic carbon and time horizon were analyzed.

Regarding the origin of the reviewed papers, since co-authors from different countries are often involved, the first author's organization countries were considered for comparison. The large majority of the reviewed paper were from the United States (36.49%). Many reviewed studies, in fact, were carried out within CORRIM. A quite large number of studies came from Scandinavian countries (Finland, Sweden and Norway) which overall accounted for 28.38%. The remaining EU countries accounted for 21.62%. In total 50% of the analyzed papers were from EU and 44.59%



from United States and Canada. The remaining 5.41% included papers from Australia, Brazil, Japan and China.



**Figure 1.16** Ripartition of the years of publication of the review papers.

More than three quarters of the reviewed papers (78.38%) were published from 2008 to 2014, in same percentage (39.19%) for the two periods 2008-2010 and 2011-2014. The remaining 21.62% of the papers were published between 1996 and 2008.

The results of the review are presented in the following paragraphs. The key aspects outlined are described in the following paragraphs and regard the following aspects: case studies and data availability; environmental benefits of replacing fossil fuels with bio-energy; carbon neutrality; harvesting, conversion and distribution phases; forest management and dynamic LCA.

### 1.6.2.1 Case studies and data availability

Cherubini and Strømman reviewed the state of the art of life cycle assessment of bio-energy systems, both as transportation fuel (bio-ethanol and bio-diesel) and for heat and power production (Cherubini and Strømman, 2011). They found that the majority of the analyzed papers focused on bio-ethanol and bio-diesel production. The number of studies evaluating the environmental performances of biomass for heat and power production was slightly lower than that for transportation bio-fuels. The authors justified the result by observing that, while electricity and heat can be produced by a variety of renewable sources (wind, solar, hydro, biomass, etc.), the only alternative to fossil resources for production of fuels and chemicals is biomass.

The Life Cycle Assessment approach is not limited to the global warming impact category. Although almost the totality of the reviewed studies included Global Warming Potential in the evaluation, some LCA studies have also examined life cycle impacts on other environmental categories, including local air pollution, acidification, eutrophication, ozone depletion, land use (Merra et al., 2001).

Moreover it has emerged that there is heterogeneity in the evaluation methods, regarding the use of different indicators, system boundaries, allocation procedures (Merra et al., 2001), functional units and reference systems. This means that outcomes are often not immediately comparable and of difficult interpretation.

This highlights a critical limit of LCA studies recognized by the ISO 14040, which is that LCA only addresses the environmental issues that are specified in the goal and scope of the study. Therefore, it is not a complete assessment of all environmental issues of the product system under study.

Furthermore, one of the limitation outlined by the ISO 14040, is the lack of availability of collected inventory data appropriate and representative for each impact category. Moreover, the LCI data available are often evaluated as global or European average values. From the literary review, it emerged that a small number of Italian case studies about this topic exist (Cespi et al., 2014; Valente et al., 2011). Critical issues outlined by the ISO are also associated with the limited development of characterization models, inadequate LCI data quality which may, for instance, be caused by uncertainties or differences in allocation and aggregation procedures.

#### 1.6.2.2 Environmental benefits of replacing fossil fuels with bio-energy

The large majority of the reviewed studies highlighted the environmental benefits deriving from replacing fossil fuels with bio-energy from renewable biomass sources, which, according to Cherubini and Strømman, represent the main driving forcing for promoting the production and use of bio-energy (Cherubini and Strømman, 2011).

Producing cellulosic bio-fuels from wood resources that are currently wasted or are not of adequate quality for other uses can substantially reduce emissions by substituting fossil fuels that have a disproportionately larger impact (Lippke et al., 2012; Pingoud et al., 2010).

It was highlighted that the benefits of using wood-based energy are multiple and include not only emissions reduction from the combustion of fossil fuels, but also the utilization of locally available raw materials and to some extent, the reduction of carbon emissions owing to the decomposition of forest residues left after final felling (Alam et al., 2010).

Several studies have demonstrated the overall benefit for the environment associated with the use of wood instead of traditional fossil fuels such as coal and natural gas (Cherubini et al., 2009; Lippke et al., 2011a; Sathre and Gustavsson, 2012; Sathre and O'Connor, 2010).

A recent study of Puettmann and Lippke simulated different fuel-substitution scenarios and proved that all of them resulted in a decreased GWP. Moreover it was shown that larger benefits were obtained producing heat instead of electricity, since using woody biofuel for electricity production

was somewhat less effective in lowering carbon emissions than when it was used for heat energy (Puettmann and Lippke, 2012).

Reed et al., 2012 analyzed the fossil emission reduction when combusting pellets compared with natural gas and found that the reduction varied from 123% to 56% based on the type of allocation adopted.

Emission reductions were also estimated on a country level. A recent study evaluated the net emission reductions in Japan between 2005 and 2050 through the massive use of wood resources for energy (Kayo et al., 2011).

However, a key issue emerged by the analysis of studies about the emission reduction deriving by the use of bio-energy: the resulting GHG emissions savings are largely variable with the fossil reference system considered. For example, if electricity in the fossil reference system is produced from natural gas, this option has a GHG emission factor of 120 g CO<sub>2</sub>-eq./MJ. By contrast, if it is produced from coal, the GHG emission factor is 237 g CO<sub>2</sub>-eq./MJ. Thus for the comparison the definition of the fossil reference system has a strong importance (Cherubini, 2010).

### 1.6.2.3 Carbon neutrality

The evaluation of the environmental benefits in terms of emission reduction deriving by replacing fossil fuels with bio-energy is based on some methodological assumptions.

There is a primary distinction between fossil fuel and biofuel CO<sub>2</sub> emissions which is related to the source of the carbon stored in them. The use of fossil fuels releases geologic carbon that has been stored in the ground, and those emissions represent a net addition of CO<sub>2</sub> to the atmosphere (fossil fuel-derived CO<sub>2</sub> emissions). Bio-energy uses wood or wood residue derived from timber harvest operations. Trees sequester atmospheric carbon dioxide as they grow and burning biofuels simply releases this sequestered carbon dioxide back into the environment (biogenic CO<sub>2</sub> emissions) (Bergman and Bove, 2010). With a sustainable forest management, where removals plus decomposition of dead and dying residuals do not exceed growth from one rotation to the next, the net addition of CO<sub>2</sub> into the atmosphere will be null and the forest will remain carbon neutral (Lippke et al., 2010).

The PAS 2050:2011 defines “fossil emissions” as those that are released through the combustion or decomposition of fossilized material (e.g., coal, oil and natural gas), “biogenic emissions” as those that are released through combustion or decomposition of biomass (i.e., material of biological origin) (BSI, 2011).

Based on the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010) and the EPA accounting framework (EPA, 2011), the impact on global warming is entirely attributed to fossil GHG emissions while biogenic emissions are considered to

be carbon neutral and are not reported in the LCA indicators.

As in the Kyoto Protocol approach, in the LCA approach the impact of bio-energy on global warming is based on the carbon neutrality assumption, based on the idea that the release of carbon dioxide during the conversion of biomass to energy is balanced by the carbon sequestered within that biomass.

In carbon accounting terms, carbon sequestration during biomass growth is accounted for as a negative emission. The net GHG emissions from biologically based energy products is evaluated by subtracting the amount of CO<sub>2</sub> taken up during biomass growth in the first stage of the product life cycle from the amount of CO<sub>2</sub> (including biogenic) released to the atmosphere during all life cycle stages of the product (Brandão et al., 2013). Among the new and developing approaches, the ISO 14067 (ISO, 2013a) and GHG Protocol (WRI and WBCSD, 2013), as well as the revised Publicly Available Specification (BSI, 2011), require that the biogenic contribution be excluded from the accounting although it may be calculated and reported separately.

The analysis of the scientific literature on the Life Cycle Assessment shows that, in most of the cases, as far as the global warming is concerned, biomass is considered to be carbon neutral (Cherubini et al., 2009; Helin et al., 2013; Hubbard and Bowe, 2010; Katers et al., 2012; Lippke et al., 2011b, 2010; McKechnie et al., 2011; McManus, 2010; Oneil et al., 2010; Oneil and Lippke, 2010; Routa et al., 2012a, 2012b; Werner et al., 2010; Whittaker et al., 2011; Wilson, 2010a, 2010b, 2010c).

The assumption of carbon neutrality:

- in the Kyoto Protocol approach simply attributes an impact on global warming equal to zero ignoring the emissions generated in other processes associated with the wood products supply chain;
- in the LCA approach the impact on global warming of the combustion is assumed to be equal to the benefit of carbon sequestration and the net impact is associated with the remaining phases of the life cycle.

The assumption of carbon neutrality has been widely adopted although it has been recognized that in some cases (i.e. in presence of catastrophic wildfire or pathogen outbreaks) this assumption needs to be examined in greater detail because forest carbon may deviate substantially from a sustainable management regime (Oneil and Lippke, 2010).

Considering the combustion of wood fuel as carbon-neutral in this manner is consistent with many groups overseeing environmental concerns (BSI, 2008; EPA, 2003; IPCC, 2013; Wilson, 2010a, 2010b). Furthermore the CORRIM research protocol treats forests under sustainable management as carbon neutral (Oneil et al., 2010).

Based on the carbon neutrality assumption, when biomass is combusted the resulting CO<sub>2</sub> emission is not accounted for as a GHG because C has a biological origin and combustion of biomass

releases almost the same amount of CO<sub>2</sub> as was captured by the plant during its growth. However, combustion reactions cause emissions of other GHGs like N<sub>2</sub>O and CH<sub>4</sub>, which must be estimated and accounted for in the GHG balance (even if their contribution is expected to be small). Furthermore, some studies have shown that, given the large quantities of pollutants released, combustion can have a high impact on photochemical smog and human toxicity (Cespi et al., 2014; Solli et al., 2009).

#### 1.6.2.4 Harvesting, conversion and distribution phases

The environmental impacts of bio-energy are not only associated with the combustion phase but also with other phases of the LCA, including forest operation, logistics and distribution of the final product. The conversion of forest residuals to bio-energy requires various inputs from nature (the atmosphere) and industry (the technosphere). Hence, the overall environmental footprint associated with the production of bio-energy includes all the resources used, emissions and waste generated during the process of biomass growth, collection and conversion into biofuel. All these processes require energy, both heat (supplied with natural gas or oil) and electricity (usually taken from the grid), which results in GHG emissions which usually have a significant influence in the final balance (Cherubini, 2010).

There are some studies carried out in the 90's about the environmental impacts of forest operations. One of these evaluated the GHGs emissions due to use of primary energy in silvicultural and forest-improvement work, wood harvesting, and timber transportation in Finland (Karjalainen and Asikainen, 1996). The study showed that silvicultural and forest-improvement work caused smaller emissions than did timber cutting, haulage or long-distance transportation.

Another study about the environmental impacts of forest operations compared two different types of forest management: the first was a clear cutting and shelterwood cutting in forest-management systems based on even-aged management; and the second one included mechanized and motormanual operations for felling and bucking. It was found that final felling in the form of creation and removal of shelterwood gave rise to higher emissions of CO<sub>2</sub> and NO if compared with clear cutting. The explanation that the author gave was that the shelterwood system involves felling in several stages, with productivity in each stage being lower than in clear cutting (Berg, 1997).

Harvesting operations include a large number of equipments and many sets of different forest operations based on the characteristics of the area to harvest.

As a consequence of different log size, different transport distances in the forest, and, in particular, different transport distances from the pile to the factory, there are also large variations in emissions from forestry operations (Michelsen et al., 2008).

Biomass is subject to transportation in many points of the supply chain, within the supply chain or to the final users, by means of suitable transport means (e.g. trucks, ships, rails). From the literary review, contrasting conclusions have been reached about the impact of transportation on the whole life cycle assessment of bio-energy. According to Cherubini et al., 2010 this step usually has a small influence in the GHG balance if the fuel is used within a range of 200–300 km, while it may become relevant if a transoceanic boat transport takes place.

Conversely, another study asserted that transport was one of the major energy-consuming sectors and thus a significant source of carbon dioxide emissions in the bio-energy balance (Karjalainen and Asikainen, 1996).

The distance traveled from the site of acquisition of the raw material to the production site may play an important role in the overall carbon footprint (Berg, 1997; Heinimann, 2012; Karjalainen and Asikainen, 1996; Michelsen et al., 2008; Solli et al., 2009). The critical distance after which this impact becomes important may vary case by case.

#### 1.6.2.5 Forest management

Many of the reviewed papers have studied the relationships between a sustainable forest management and the mitigation of climate change. Based on the IPCC Guidelines, organic C is stored in five different pools: aboveground vegetation, belowground vegetation, dead wood, litter and soil (IPCC, 2006). Harvested Wood Products (HWP) have also been introduced in the Kyoto Protocol accounting.

Human activities of forest management alter carbon stocks transferring carbon from one to the other. Forest management practices have an impact on C stocks in biomass and on the annual supply of products and their mix. Basically, according to IPCC, harvesting, if on the one hand reduces C stock in forest, on the other hand increases HWP C stock, which acts as a C sink as well, contributing to lower the atmospheric amount of C (Pingoud and Lehtilä, 2002). Pingoud et al., 2001 presented empirical inventories of some HWP C stocks and their changes in Finland (Pingoud and Lehtilä, 2002). Many old and recent studies have focused on the evaluation of HWP carbon stocks based on the IPCC methods (Dias et al., 2012, 2009; Hashimoto et al., 2002; Marland et al., 2010; Pingoud et al., 2001; Skog and Nicholson, 1998; Winjum et al., 1998).

Given the high number of factors in forest dynamics which can potentially influence global warming, many of the analyzed papers have focused on how to optimize forest management in order to the environmental benefits (Hennigar et al., 2008). For example Werner et al., 2010 presented an integral model-based approach to evaluate the GHG impacts of various forest management and wood use scenarios. Their approach allowed to analyze the complex temporal and

spatial patterns of GHG emissions and removals including different forest management and wood use strategies.

Many studies agreed that an active forest management increases the efficacy in the mitigation of climate change. In a simulation study the effects of intensifying the management of 15% of the Swedish forest land was investigated on potential future forest production over a 100-year period. It was found that in the long term standing volumes in Swedish forests would significantly increase as a result of improved forest management without significantly affecting environment conservation values (Nilsson et al., 2011).

Liu and Han, 2009 compared the effect on carbon stock in forest and wood products in a high harvest scenario with the same effect in a no-harvest scenario. It was found that the amount of carbon stored in the forest and wood products combined was more stable in the high harvest scenario than in the no-harvest scenario. The modeling results showed that an important way to reduce global carbon emissions is through sustainable forest management and timely transfer of carbon to wood products. This maximizes overall carbon storage in the forest and wood products combined.

According to some studies there are trade-offs between sequestering C stocks in forests and the climatic benefits obtained by sustainable forest harvesting and using wood products to displace fossil C emissions (Kayo et al., 2011; Pingoud et al., 2010).

It was agreed that mechanisms to reduce CO<sub>2</sub> emissions to the atmosphere should combine many strategies: storage of C in the biosphere; storage of C in forest products; use of bio-fuels to displace fossil-fuel use; use of wood products which often displaces other products that require more fossil fuel for their production (Schlamadinger and Marland, 1996).

Lastly, recommendations were formulated about the optimization of forest management to maximize carbon benefits (Werner et al., 2010): (1) generate the maximum possible, sustainable increment in the forest, taking into account biodiversity conservation as well as the long term preservation of soil quality and growth performance; (2) continuously harvested this increment; (3) process the harvested wood in accordance with the principle of cascade use, i.e. first be used as a material as long as possible, preferably in structural components; (4) use waste wood that is not suitable for further use to generate energy. According to the authors, political strategies to solely increase the use of wood as a bio-fuel cannot be considered efficient from a climate perspective.

#### 1.6.2.6 Dynamic LCA

In the LCA framework how to consider carbon stock is still object of debate. Based on the PAS 2050:2008 carbon storage is defined as retaining carbon of biogenic or atmospheric origin in a form other than as an atmospheric gas where biogenic carbon” is defined as “derived from biomass,

but not fossilized or from fossil sources and biomass is defined as material of biological origin, excluding material embedded in geological formations or transformed to fossil (BSI, 2008).

Related to the concept of carbon storage there is the concept of “delayed emissions” which refers to when emissions arising from the use phase of a product, or from its disposal, occur after the first year following the formation of the product but within the 100-year assessment period (BSI, 2008). The impacts of temporary carbon storage and removals are usually neglected in current environmental assessment of products where only the impact of fossil-fuel based GHG emissions is included (Brandão et al., 2013). According to the ILCD handbook temporary carbon storage and delayed emissions should not be considered in LCA unless the goal of the study clearly warrants it. In the case the goal of the study requires to evaluate them, any delayed GHG emission should be treated on the same basis as temporary carbon storage. To account for a delayed emission, a credit should be given reflecting the weighted average time the emissions are present in the atmosphere during the 100-year assessment period, based on the number of years the emission is delayed by, up to 100 years. Emissions occurring beyond 100 years (before 100 000 years) from the time of the study are inventoried separately as long term emissions. According to Lippke et al., 2010, the transfer of C from the forest to products is a negative emission relative to the positive emissions from the processing energy required to produce the products and hence becomes an offset against other carbon emissions during the product life cycle.

The problem of quantifying timing in LCA is becoming more and more important within the LCA framework. As observed by Brandão et al., 2013, although the net exchange may be the same, their different timing with respect to the order of uptake and release of carbon will lead to different trajectories of atmospheric CO<sub>2</sub> concentrations.

Some methods have been proposed for considering the dynamics of the carbon cycle in assessing sequestration and temporary storage of carbon and delayed GHG emissions.

The two most popular methods in the literature are the Moura-Costa method and the Lashof accounting method (Sathre and Gustavsson, 2012). These methods evaluate the impact on global warming using the radiative forcing approach and produce equivalence factors that can be used to account for carbon storage based on the number of years the carbon is sequestered.

The literary review has highlighted the complexity of forest dynamics which can affect climate change. In LCA natural dynamics occurring in the forest are generally not considered in the evaluation. This lack of spatial and temporal dimensions in the LCI results is also recognized to be a critical issue by the ISO 14040. Credit is effectively given for biomass used for energy without acknowledging that it may take many decades to cancel the “carbon debt” created by the reduction of the forest carbon stock (Brandão et al., 2013) and that there is a time lag between combustion and regrowth, and while the CO<sub>2</sub> is resident in the atmosphere it leads to an additional RF (IPCC, 2013).



This problem is becoming more and more important at international level and was the main focus of the workshop organised by the European Commission's Joint Research Centre in Ispra, Italy, in October 2010. It was also for the first time introduced in an IPCC Report. The 5<sup>th</sup> IPCC Report not only addresses the problem, but it also extends the knowledge and the available means to perform the evaluation (Myhre et al., 2013), providing AGWP, lifetimes and Radiative Efficiency for all the GHGs. Furthermore the IPCC Supplementary material chap.8 specifies the formulas to evaluate the AGWP and the radiative efficiency.

In the scientific literature the topic has been addressed in some recent papers (Brandão et al., 2013; Courchesne et al., 2010; Helin et al., 2013; Levasseur et al., 2012, 2010). A dynamic LCA approach has been lately developed to account for the timing of the emissions in LCA which considers the temporal distribution of GHG emissions over the life cycle of a product. The dynamic LCA has recently been adopted to evaluate the impact of renewable resources (Kendall et al., 2009; Kirkinen et al., 2008; Levasseur et al., 2010; O'Hare et al., 2009). This approach considers the temporal distribution of GHG emissions over the life cycle and calculates their impact on radiative forcing using dynamic characterization factors, which consist of the absolute GWP integrated continuously through a fixed time horizon. These dynamic characterization factors are then used to substitute for the characterization factors used in the traditional LCA (Brandão et al., 2013). Cherubini et al., 2011a, 2011b applied the radiative forcing approach to calculate the integrated impact of carbon uptake during biomass growth in the forest with GHG emissions during biomass burns using an analytical model. However, no auxiliary life cycle inputs for harvesting and biomass processing were considered in this study.

Furthermore Zanchi et al., 2010 described the concept of carbon neutrality factor (CN) reflecting the extent to which various bioenergy systems are carbon neutral over a chosen time period. Some alternative approaches to account for biogenic carbon uptake and emissions include the indicator  $GWP_{bio}$ , developed to assess the climate change impact of biogenic CO<sub>2</sub> emissions while considering the dynamics of vegetation regrowth (Brandão et al., 2013). Modifications of the GWP and GTP for bioenergy ( $GWP_{bio}$  and  $GTP_{bio}$ ) have been developed in order to quantify the temporal discrepancy between emissions and removals (Cherubini et al., 2012, 2011a). The  $GWP_{bio}$  gives values generally between zero (current default for bio-energy) and one (current for fossil fuel emissions).  $GWP_{bio}$  and  $GTP_{bio}$  have been used in only a few applications and more research is needed to assess their robustness and applicability (IPCC, 2013).

## **1.7 Motivation of the study**

It has been shown how the topic of the energy production from woody biomass is crucial in International, European and National politics for the greenhouse gas emissions reduction and is

supported by many forms of incentives.

These politics have been intensifying in the last period, setting more and more ambitious objectives for the near future. As a consequence of these politics it is expected that this sector will considerably grow in the next years.

For this reason, it is of fundamental importance to appropriately determine its environmental impacts. The internationally recognized approach to evaluate the environmental sustainability of products is called Life Cycle Assessment (LCA) and consists in the evaluation of all the inputs, outputs and the potential environmental impacts throughout the life cycle from the acquisition of the raw materials from the environment, including logistics, forest operations, distribution of the final product until combustion.

From the analysis of the scientific literature the following limitations have been outlined:

- There is heterogeneity in the evaluation methodologies, in particular regarding the system boundaries because many studies adopt an approach limited to the direct emissions without taking into consideration the emissions associated with the whole life cycle.
- There are a few studies about the impacts of forest operations, especially applicable to the Italian reality.
- The carbon neutrality assumption is used in the majority of the LCA studies of biomass. In this way it is assumed that the carbon dioxide emissions associated with the combustion equal the carbon dioxide absorbed from the atmosphere for the biomass growth and they are neglected. However it is not taken into account that, contrarily to carbon dioxide, the other pollutants emitted during combustion which have a potential impact on human health, can not be offset in any way.
- The main limitation of the LCA is that it is a static approach. All the emissions and absorption are considered instantly released at the beginning of the evaluation period. In this way the LCA result is a picture of the environmental impacts at a specific point in time. However the ways the carbon dioxide absorption occurs in forest can be very different in function of many factors, as: the forest management, the type of species, the age of species, the rotation period. Since the impact on global warming is evaluated through the Radiative Forcing, which is a function of time, the temporal aspect plays a fundamental role in the impacts evaluation. Moreover the ways the residues decompose in forest is variable. This aspect is not normally considered in LCA but their decomposition over time releases delayed greenhouse gas emissions and this factor has a potential impact on climate change.

To take into account the delayed emissions over time and the absorption dynamics it is necessary to extend the traditional LCA approach adding the temporal aspect.

To determine the real impact of bio-energy on global warming it is necessary to consider the

impact on Radiative Forcing and its cumulative effect over time.

Therefore, the following questions were formulated:

- What is the impact share of forest operations of harvesting and processing biomass on the total global warming impact?
- How does the importation of wood from abroad increase the environmental impact of transportation compared to a short supply chain?
- What is the impact of combustion on local atmospheric pollution?
- How can we incorporate the dynamics of carbon sequestration and wood decomposition into the LCA framework?
- If the dynamics of natural phenomena are included in the LCA, can wood really be considered carbon neutral?

Based on the research questions, the following objectives were defined:

- 1) Perform a Life Cycle Assessment of wood products for bio-energy to evaluate their environmental impacts with the following specific targets (targets are subdivided for the specific phases of the life cycle):
  - Raw materials supply:  
Evaluation of the global and local impact of the transportation associated with the importation of raw materials from abroad (long supply chain) compared to produce them locally (short supply chain).
  - Production  
Evaluation of the environmental impact of the forest operations of harvesting and processing the wood.
  - Distribution  
Evaluation of the contribute of transportation in function of different logistics scenarios based on the morphology of the site and the means of transportation adopted.
  - End of life:

Evaluation of the global and local impact of the wood combustion to produce bio-energy.

- 2) Incorporate dynamic functions of greenhouse gases release and uptake into the LCA framework to develop a “dynamic LCA” for the following aspects:
  - Carbon sequestration in forest
  - Evaluation of the effect of forest management, considering the following factors: type of species, disturbances, timeframe, type of management.
  - Decomposition of residues left in forest.

## 1.8 Case studies

To meet these objectives two different wood products were chosen and analyzed through the following case studies:

- 1) The first case study is the LCA of firewood performed in the Northern-East of Italy. The focus of this study was to quantify the impact of the importation of the raw material from abroad on different impact categories and to compare the *long and the short supply chain*. Also the *local* impact of the wood combustion was analyzed.
- 2) The second case study is the LCA of wood chips for bio-energy performed for the U.S. Pacific Northwest. This study was performed at the School of Environmental and Forest Science, University of Washington, Seattle, United States. This study focused on the impact of different types of forest operations and logistics schemes. This study also addressed the issues of the allocation and of the avoided impacts within the LCA.

Afterwards, the problem of how to incorporate dynamic functions into the LCA framework was addressed. This led to the development of a methodology to perform a “dynamic LCA” to incorporate the dynamics of carbon sequestration and decomposition of wood into the LCA.

A new methodology has been studied and proposed which considers the radiative forcing of the different sources of emissions and the decay of greenhouse gases to the atmosphere.

Through this approach it was possible to discuss the truthfulness of the carbon neutrality assumption.

## Chapter 2

### The supply chain

#### 2.1 The supply chain of wood products for bio-energy

##### 2.1.1 Feedstock

Biomass for bioenergy purposes can be obtained in two ways: from residues and from dedicated energy crops. Biomass residues and wastes are materials of biological origin arising as by-products and wastes from agriculture, forestry, forest or agricultural industries, and households (Hoogwijk et al., 2003) and are not produced for use as an energy resource. On the contrary, dedicated bioenergy crops are specifically grown for energy purpose. The two main products used for bio-energy are:

- firewood;
- wood chips.



**Figure 2.1** *Firewood and wood chips for bioenergy.*

A third product, pellet, is commonly used for bio-energy but it is outside the scope of this dissertation and it will be omitted from the analysis.

##### 2.1.2 Working phases and working systems

As far as the forest operations are concerned, it is possible to differentiate between the following working phases (AEBIOM, 2009):

- Harvesting: it consists of cutting the standing tree from its stump so that the tree falls to the ground;
- Processing: delimiting (removing branches from the trunk and topping it) and cross-cutting (cutting the trunk to predetermined lengths);

- Blindling: transporting wood from felling site to extraction routes;
- Hauling: transporting wood along extraction routes to the landing site;
- Debarking: partially or completely removing the bark from a log;
- Transporting: moving wood using forest roads and public roads;

Transforming: reducing wood for fuel destination (cutting, splitting, chipping).

Many sawlog operations utilize a harvesting method called whole tree harvesting, that allows the removal of limbs and tops to be mechanized at a landing and reduces the requirements for subsequent slash disposal across the site.

There are two main working systems in forest harvesting operations:

- Short wood system: processing is completed on the falling site in the forest and commercial logs are hauled;
- Full tree system: after felling the whole tree is hauled and processing is performed either on the forest road or on the landing site.

The working machines used in forest operations and their technical characteristics are listed in Table 2.1.

### ***2.1.3 Firewood production***

The firewood production includes sawing and splitting the wood to transform it in wood logs. The sawn and splitter reduces the wood width by breaking the log by a mechanical force applied parallel to the fibres. The sawn and splitter combines the two operations of sawing and splitting allowing an elevated process automation and a high productivity. They are endowed with electric or spark-ignition engine (up to 55 kW) and can work logs up to 6 m long and 60 cm of diameter and can produce more than 12 t/h of material.

Processing hardwood requires more power than processing softwood and all types of wood can more easily be split when fresh rather than seasoned.

### ***2.1.4 Wood chips production***

A chipper is a machine that is especially built to reduce wood to chips and can either be stationary or mounted on a carriage, on a trailer, on a truck or on the rear three point hitch of a tractor. It can be equipped with its own engine or activated by the tractor power take off. Depending on the chipping unit it is possible to differentiate between:

**Table 2.1** Technical characteristics of common working machines used in forest operations (AEBIOM, 2009).

Machine	Productivity [m3/h]	Fuel cons. [l/h]	Load. cap. [t]	Max traction power [daN]	Diameter [cm]	Max negotiable slope [%]
Chainsaw	In high forest thinning 1-1.2	0.6-1	-	-	-	-
	In high forest main felling 2-2.5					
	In coppice average cond. 0.4-0.7					
	In coppice good cond. 0.8-1.8					
Tractor and winch	In high forest 2.5-6 (solid m3/h)	4-9	-	-	-	-
	In coppice 3-7 (stacked m3/h)					
Tractor and trailer	5-12 (solid m3/h)	5-10	5-15	-	-	-
Cable crane with mobile tower yarder - Light	3-6 (solid m3/h)	5-6	-	2000	-	-
Cable crane with mobile tower yarder - Medium	3-12 (solid m3/h)	6-10	-	5000	-	-
Harvester	8-20 (solid m3/h)	11-16	-	-	Max cutting diameter 65-70	Wheels 35%
					Max delimiting diameter 45-60	Trucks 60%
Forwarder	12-20 (solid m3/h)	7-11	10-14	-	-	30-35%
Hybrid harvester	10-15 (solid m3/h)	10-12	-	-	Max cutting diameter 55	45-50%
					Max delimiting diameter 50	
Skidder	8-12 (solid m3/h)	6-10	skid. cap. up to 3	-	-	20%
Tractor-mounted processor	10-15 (solid m3/h)	4-5	-	-	Max cutting diameter 48	-
					Max delimiting diameter 40	
Excavator-based processor	15-40 (solid m3/h)	15-17	-	-	Max cutting diameter 65	-
					Max delimiting diameter 60	
Chipper – Small power	2-3 t/h	5-8	-	-	< 20	-
Chipper – Medium power	4-7 t/h	10-14	-	-	20 < d < 30	-
Chipper – High power	13-20 t/h	34-38	-	-	> 30	-
Saw and splitter	-	-	-	-	25-60	-
Truck and trailer (log transport)	-	2.5-3.5 km/l	18-20	-	-	-
Truck and trailer (wood chips transport)	-	2.5-3.5 km/l	20-22 (85- 90 bulk m3)	-	-	-

- Disc chippers: the chipping unit consists of a heavy flywheel on which are radially mounted from two to four knives. The material comes into contact with the disc at an angle of 30-40 degrees to the plan of the disc and the rotating knives cut progressive slices from the wood that breaks up into chips whilst being cut. Chip size is usually between 0.3 and 4.5 cm and can be modified by an adjustable bed knife;
- Drum chippers: bigger and more powerful than disc chippers, these chippers can easily work both logs and harvesting residues. The chipping unit consists of a steel cylinder with up to 12 knives installed in tangential position. Chip size is more heterogeneous with length with lengths up to 6.5 cm;
- Feed screw chippers: chipping is provided by a big worm of decreasing section with sharp edges that rotates on a horizontal axis. These machines, which are not particularly widespread, can mostly process full trees or logs and produce bigger chips (up to 8 cm) compared to disc and drum chippers.

According to the required power, three categories can be identified:

- Small power: usually installed on the rear three point hitch of a tractor or on a trailer, these chippers are powered by the tractor power take off or by an independent engine (~50 kW). They can only process small diameters (20 cm max) and can produce no more than 20 t/day;
- Medium power: trailer-mounted, usually with independent engine (50-110 kW) they can chip diameters up to 30 cm and produce up to 50t/day;
- High power: installed on trailers or on trucks, these chippers are sometimes activated by the truck's engine but normally they are provided with an autonomous engine (>130 kW); they can chip big diameters (>30 cm) and easily produce more than 60 t/day.

The sieve is an important tool which makes possible the selection of chips during the expulsion phase, thus refining the material.

#### 2.1.4.1 Volume terminology

The volume of wood fuels, whether densified or not, varies according to the shape, size and arrangement of the single pieces of wood. Thus, specific unit of measure were introduced in order to facilitate their measurement.

The solid cubic meter (m<sup>3</sup>) is used with reference to the volume that is entirely occupied by wood. This unit of measurement is commonly used for timber.

For wood fuels, the stère is typically used. It refers to the volume occupied by wood as well as by air space, considering void space as filled space. The steric volume is defined as the ratio between filled and void volume.



Table 2.2 Terminology for of measure commonly used for wood fuels volume.

English	Symbol	Italian	Symbol
Solid cubic meter	solid m <sup>3</sup>	Metro cubo	m <sup>3</sup>
Bulk cubic meter	bulk m <sup>3</sup>	Metro stero riversato	msr
Stacked cubic meter	stacked m <sup>3</sup>	Metro stero accatastato	msa

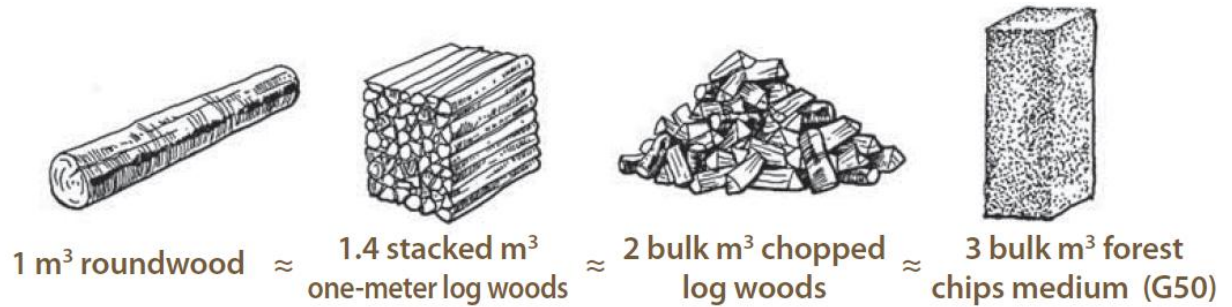












Figure 2.1 Unit of measure commonly used for wood fuels volume.

Table 2.3 Roundwood/log woods/wod chips conversion rates

Assortment	Roundwood	One-meter log woods	Chopped log woods		Wood chips	
						
	m <sup>3</sup>	stacked m <sup>3</sup>	stacked m <sup>3</sup>	bulk m <sup>3</sup>	fine (G30) bulk m <sup>3</sup>	medium (G50) m <sup>3</sup>
1 m <sup>3</sup> roundwood 	1	1.4	1.2	2.0	2.5	3.0
1 stacked m <sup>3</sup> one-meter log woods 	0.7	1	0.8	1.4	1.75	2.1
1 stacked m <sup>3</sup> chopped log woods	0.85	1.2	1	1.7		
1 bulk m <sup>3</sup> chopped log woods 	0.5	0.7	0.6	1		
1 bulk m <sup>3</sup> forest chips fine (G30) 	0.4	0.55			1	1.2
1 bulk m <sup>3</sup> forest chips medium (G50)	0.33	0.5			0.8	1

The stacked cubic meter (stacked m<sup>3</sup>) is the unit of measurement used for neatly-stacked log woods. The bulk cubic meter (bulk m<sup>3</sup>) is the unit of measurement used for log woods and, more typically, wood chips. The unit of measure commonly used for wood fuels volume are represented in Figure 2.3

### ***2.1.5 Wood seasoning and drying***

The material needs to go through a seasoning phase, with an intermediate storage in a banking ground outside before it is chipped. During storage fresh lignocellulosic biomass gets warmer due to the respiration processes of still/living parenchymal cells. Such processes stop on reaching 40°C. The further increase in the temperature of the wood mass can be ascribed to the metabolism of fungi and bacteria. While fungi can survive up to a temperature of about 60°C, the activity of thermophilic bacteria begins at 75 to 80°C. Under special circumstances wood mass warming can even reach a temperature of about 100°C. Over 100°C some thermochemical transformation processes can begin and lead, although this only happens very rarely, to spontaneous combustion phenomena. Such phenomena generally occur with fine wood material (fine sawdust) and bark. Due to the intensification of the metabolic activities of fungi and bacteria the decomposition of the wood substance can occur and, consequently, there is a loss of fuel organic mass. In order to minimize such losses, biological activity must be kept as much as possible under control.

The best way to store and season wood chips is to lay them on a waterproof surface (cement or asphalt) protected by a cover located in a sunny and ventilated site. Seasoning must take place in summer, when the free energy supply from the sun and wind, which favours the natural drying of the wood, is maximum.

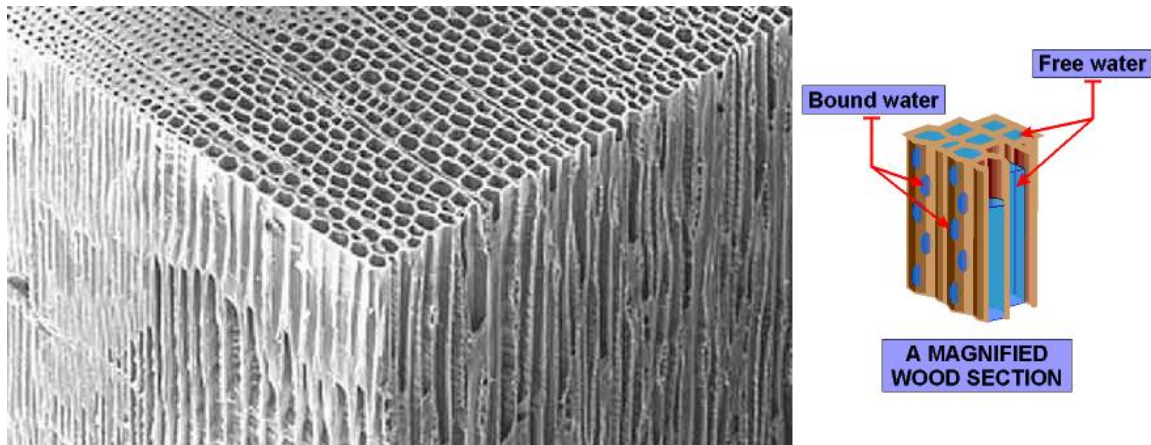
The time required to reach a moisture content of 20% varies with the weather, varying from 6 to 7 months. The M 30% value is defined as “suitable for storage”. Below this limit wood chips are classified as fit for storage without any biological stability problems (ONORM M 7133).

The seasoning time can be strongly reduced by using a drying system. Common drying systems include drying prompted by the heat of fermentation processes, forced ventilation using air preheated by solar energy, forced ventilation systems and hot air drying. Thank to these systems it is possible to reduce the moisture content in a few weeks in spring/summer.

#### **2.1.5.1 Water in wood**

Wood is not typically found in the oven-dry state but it has a moisture which may vary from 60 to 15% depending on the duration of open-air seasoning. Wood is a porous and hygroscopic material and, due to its chemico-histological structure, it has two different types of porosity:

- the macroporosity created by the cavities of the conductive vessels and by parenchymal cells containing free (or imbibition) water;
- the microporosity of the actual wood substance (mainly cellulose, hemicelluloses and lignin) which always contains a certain amount of bound (or saturation) water.



**Figure 2.2** Representation of micro and macroporosity in wood.

When the tree is harvested, wood begins to lose water. First, imbibition water evaporates from the outermost and, later, innermost parts of the trunk. At a certain point, all the free water evaporates and the saturation water reaches a dynamic equilibrium with the outward moisture, reaching a value below 20%.

During log wood and wood chips seasoning, and up to a moisture content of 23% ( $u < 30\%$ , fibre saturation point) no shrinkage in the volume of the single pieces and piles occurs. Up to this point, wood has only lost its free (or imbibition) water. Later, when wood begins to lose its bound (or saturation) water as well, there occurs shrinkage in volume that, although it may vary depending on the wood species, is usually of 13%. Contrariwise, if saturation water increases, wood will swell.

The shrinkage of the single pieces in a log woods stack or wood chips pile entails an overall decrease in the volume of the pile that is almost always lower than that of the single pieces.

From an applicative point of view, any variations in volume (shrinkage and swelling) registered within a 0 to 23% interval (hygroscopic field) must be taken into account for a correct calculation of the mass density, whether steric (with water) or not, and for the energy density of fuels.

#### 2.1.5.2 Moisture content

The water content present in wood is expressed in terms of moisture, which is defined on dry and on wet basis:

Moisture on dry basis ( $u\%$ ) expresses the mass of water present in relation to the mass of oven-dry wood.

$$u = \frac{W_w - W_0}{W_0} \cdot 100$$

$W_w$  = wet weight of wood

$W_0$  = oven-dry weight of wood

Moisture on wet basis (M%) expresses the mass of water present in relation to the mass of fresh wood. This measure is used in the marketing of wood fuels.

$$M = \frac{W_w - W_0}{W_w} \cdot 100$$

### 2.1.5.3 Mass density of the main forest species

The density of wood is related to its moisture content, with its minimum value for oven-dry wood. Most of the wood fuels used for bio-energy, however, have moisture contents of 13%. Mean values of mass density with moisture content 13% and 0% for softwood and hardwoods are shown in Table 2.4 and Table 2.5 respectively.

Reference density values for chopped log wood and wood chips are reported in Table 2.6 for some common species.

**Table 2.4** Softwood, mean values of mass density with moisture content (MC) 13% (Giordano, 1988).

Species [English]	Species [Italian]	Mass density MC 13% [kg/m <sup>3</sup> ]	Mass density oven-dry wood [kg/m <sup>3</sup> ]
Norway spruce	Abete rosso	450	430
Silver fir	Abete bianco	470	410
Arolla pine	Pino cembro	500	400
Douglas-fir	Abete di Douglas	510	470
Scots pine	Pino silvestre	550	510
Black pine	Pino nero	560	560
Cypress	Cipresso	600	
Stone pine	Cembro	620	
Larch	Larice	660	550
Maritime pine	Pino marittimo	680	
Yew	Tasso	700	
Aleppo pine	Pino d'Aleppo	810	

**Table 2.5** *Hardwood, mean values of mass density with moisture content (MC) 13% (Giordano, 1988).*

Species [English]	Species [Italian]	Mass density MC 13% [kg/m <sup>3</sup> ]	Mass density oven-dry wood [kg/m <sup>3</sup> ]
Willows	Salice	450	520
White poplar	Pioppo bianco	480	410
Black poplar	Pioppo nero	500	410
Speckled alder	Ontano bianco	520	
Italian alder	Ontano italiano	550	490
Black Alder	Ontano nero	560	490
Chestnut	Castagno	580	
Cherry	Ciliegio	600	
Elm	Olmo	620	640
Elder	Sambuco	620	
Birch	Betulla	650	640
Lime	Tiglio	650	520
Hazel	Nocciolo	670	560
Sycamore Maple	Acerò montano	670	
Planes	Platano	670	
Walnut	Noce	700	
Hackberry	Olmo bianco	720	
Ash	Frassino	720	670
Manna ash	Orniello	720	
Laburnum	Laburno	730	
Field maple	Acerò campestre	740	590
Beech	Faggio	750	680
Sessile oak	Rovere	760	
Black locust	Robinia	760	730
Pedunculate oak	Quercia	770	670
Rowans	Sorbo	770	
Common hornbeam	Carpino	800	750
Hophornbeam	Carpino nero	820	
Turkey oak	Cerro	900	740
Olive	Olivo	920	
Holm oak	Leccio	940	
Cornel	Corniolo	980	

**Table 2.6** *Bulk density in kg of the main solid biofuels (AEBIOM, 2009) (the equivalence 1m<sup>3</sup> roundwood = 2.43 bulk m<sup>3</sup> (volumetric index=0.41 m<sup>3</sup>/bulk m<sup>3</sup>) of wood chips has been used)*

MC%	Beech			Oak			Spruce			Pine		
	m <sup>3</sup>	chopped log wood stacked (33cm) m <sup>3</sup>	wood chips bulk m <sup>3</sup>	m <sup>3</sup>	chopped log wood stacked (33cm) m <sup>3</sup>	wood chips bulk m <sup>3</sup>	m <sup>3</sup>	chopped log wood stacked (33cm) m <sup>3</sup>	wood chips bulk m <sup>3</sup>	m <sup>3</sup>	chopped log wood stacked (33cm) m <sup>3</sup>	wood chips bulk m <sup>3</sup>
0	680	422	280	660	410	272	430	277	177	490	316	202
10	704	437	290	687	427	283	457	295	188	514	332	212
15	716	445	295	702	436	289	472	304	194	527	340	217
20	730	453	300	724	450	298	488	315	201	541	349	223
30	798	495	328	828	514	341	541	349	223	615	397	253
40	930	578	383	966	600	397	631	407	260	718	463	295
50	1117	694	454	1159	720	477	758	489	312	861	556	354

## ***2.1.6 Technologies for energy production***

### **2.1.6.1 Firewood stoves**

These machines are manually fed and their work is based almost solely on the principle of low or reversed flame. These boilers are mainly used in buildings that require a thermal power up to 50-60 kW (maximum power of 100 kW). These stoves are characterized by having modular power and combustion, regulation of the air flow input and efficiency 90%.

### **2.1.6.2 Wood chips stoves**

Many technologies of wood chips stove exist, however a detailed description of them is outside the scope of this dissertation. Stoves can be classified in:

- Bottom feedstock stoves (from 10 kW to 2.5 MW): wood chips, which must have a moisture content in the range 5-50%, are introduced from the bottom.
  
- Side feedstock stoves: fixed grid (from 25 kW): wood chips, which must have uniform size and moisture content lower than 30-35%, are introduced laterally into the combustion chamber by a screw or a pusher. The ashes produced fall into a drawer located below the grid.
  
- Side feedstock stoves : mobile grid (from 15 kW to > 20 MW): they are used both in the residential sector and in the industrial and they are suitable to use wet wood chips (M 40-50%) with high ash content.

### **2.1.6.3 District heating networks**

The heat produced from the boiler can be transported to other nearby buildings through a district heating network constituted of well insulated pipes.

A network should be designed trying to contain the length and looking for a high density of connected users, with values ranging from about 0.5 to 1 kW/m.

In district heating the primary circuit, which starts from the centralized boiler, interfaces with the users by means of a substation which transfers the heat to the circuit user both for heating and for domestic hot water.

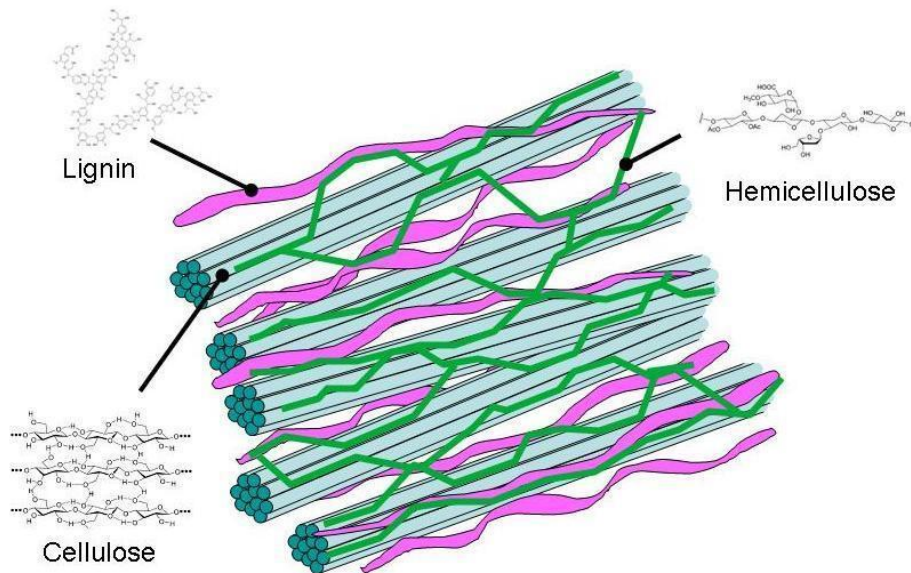
## ***2.1.7 Factors influencing wood combustion***

Wood combustion depends on biomass chemical compositions and ash content. During combustion, in fact, the chemical elements originally present in biomass are released with potential

consequences for the environment on the local and global level. To understand why some pollutants are emitted it is important to know the chemical composition of the starting material.

### 2.1.7.1 Biomass chemical composition

Wood is essentially composed of cellulose, hemicellulose, lignin, and extractives.



**Figure 2.3** Woody biomass components: cellulose, hemicelluloses and lignin.

#### **Composition of biomass** (Demirbas, 2009)

**Cellulose**  $(CH_{1.67}O_{0.83})$  It is a remarkable pure organic polymer, consisting solely of units of anhydroglucose held together in a giant straight-chain molecule. By forming intramolecular and intermolecular hydrogen bonds between OH groups within the same cellulose chain and the surrounding cellulose chains, the chains tend to be arranged in parallel and form a crystalline supermolecular structure. Bundles of linear cellulose chains (in the longitudinal direction) form a microfibril which is oriented in the cell wall structure.

**Hemicellulose**  $(CH_{1.64}O_{0.78})$  Unlike cellulose, hemicellulose consists of different monosaccharide units. In addition, the polymer chains of hemicelluloses have short branches and are amorphous. Hemicellulose (arabinoglycuronoxylan and galactoglucomannans) occurs in much shorter molecular chains than cellulose. Hemicellulose is derived mainly from chains of pentose sugars, and act as the cement material holding together the cellulose micelles and fiber. Among the most important

sugar of the hemicelluloses component is xylose. Because of the amorphous morphology, hemicellulose is partially soluble or swellable in water. Hemicellulose is largely soluble in alkali and, as such, is more easily hydrolyzed.

**Lignin** (C<sub>10</sub>H<sub>11</sub>O<sub>3.5</sub>) It consists of non-sugar type macromolecules which are polymers of aromatic compounds (alkylphenols) and have a complex three-dimensional structure. Its functions is to provide structural strength, sealing of the water-conducting system that links roots with leaves, and protect plants against degradation. Lignin is covalently linked with xylans in the case of hardwoods and with galactoglucomannans in softwoods. The basic chemical units of lignin are bonded together by a set of linkages to form a very complex matrix which comprises a variety of functional groups, such as hydroxyl, methoxyl and carbonyl, which impart a high polarity to the lignin macromolecule.

**Extractives** They are the organic substances which have low molecular weight and are soluble in neutral solvents. Extractives include terpenes, tall oil and the fatty acids, esters, and triglycerides. Resin (combination of the following components: terpenes, lignans and other aromatics), lipids, waxes, fatty acids and alcohols, terpenes, tannins and flavonoids are categorized as extractives

**Other components** Other components of biomass include: proteins, simple sugars, starches, water, hydrocarbons, ash, pectins and other compounds.

Softwoods and hardwoods differ greatly in wood structure and composition. Hardwoods have a higher proportion of cellulose, hemicelluloses and extractives while softwoods have a higher proportion of lignin. Hardwoods are denser than softwoods. The relative compositions of hardwoods and softwoods are shown in Table 2.7

**Table 2.7** Structural composition of wood (wt.% of dry and ash-free sample)

<b>Wood species</b>	<b>Cellulose</b>	<b>Hemicelluloses</b>	<b>Lignin</b>	<b>Extractives</b>
Hardwood	43-48	27-35	16-24	2-8
Softwood	40-44	24-29	26-33	1-5

Overall vegetal biomass is mainly constituted by carbon (C), oxygen (O) and hydrogen (H). Carbon is the component through whose oxidation the fuel energy is released.

Besides, further energy is supplied by hydrogen to the oxidation process which, added to the



energy produced by carbon, determines the net calorific value of the fuel. Oxygen, on the contrary, solely sustains the progression of the oxidation process.

In smaller quantities wood contains also sulphur (S), nitrogen (N), chlorine (Cl), potassium (K) and ash contents. Sulphur (S) content in solid biofuels is much lower compared to that in carbonaceous fossil fuels. Nitrogen (N) content in wood biofuels is relatively low, whereas it is much higher in cereal – particularly if we thereby include reproductive organs (grains) as well – and above all in oilseed rapes (rapeseed cake). Wood fuels are generally characterized by a rather low chlorine (Cl) content. Lastly, potassium (K) is mainly found in agricultural biofuels.

**Table 2.8** Chemical composition of solid biomass (AEBIOM, 2009).

	Weight % (d.b.)						
	C	H	O	N	K	S	Cl
Spruce (with bark)	49.8	6.3	43.2	0.13	0.13	0.015	0.005
Beech (with bark)	47.9	6.2	43.3	0.22	0.22	0.015	0.006
Poplar SRC	47.5	6.2	44.1	0.42	0.35	0.031	0.004
Willow SRC	47.1	6.1	44.2	0.54	0.26	0.045	0.004
Bark (coniferous trees)	51.4	5.7	38.7	0.48	0.24	0.085	0.019
Miscanthus	47.5	6.2	41.7	0.73	0.70	0.150	0.220
Wheat straw	45.6	5.8	42.4	0.48	1.00	0.082	0.190
Triticale (grains)	43.5	6.4	46.4	1.68	0.60	0.110	0.070
Rape cake	51.5	7.4	30.1	4.97	1.60	0.550	0.019
<b><i>From CEN/TS 14961:2005 Solid biofuels – Fuel specifications and classes. Annex C.</i></b>							
Typical values for virgin wood materials – Coniferous wood	47-54	5.6-7.0	40-44	<0.1-0.5		<0.01-0.05	<0.01-0.03
Typical values for virgin wood materials – Deciduous wood	48-52	5.9-6.5	41-45	<0.1-0.5		<0.01-0.05	<0.01-0.03
Typical values for virgin bark materials	51-56	5.9-6.5	36-43	0.3-1.2		0.02-0.20	<0.01-0.05
Typical values for virgin wood materials – Logging residues	50-53	5.9-6.3	40-44	0.3-0.8		0.01-0.08	<0.01-0.04
Typical values for virgin wood materials – Short rotation coppice	47-51	5.8-6.7	40-46	0.2-0.8		0.02-0.10	<0.01-0.05
<b><i>For comparison, fossil fuels</i></b>							
Coal	72.5	5.6	11.0	1.3	-	0.94	<0.1
Lignite	65.9	4.6	23	0.7	-	0.39	<0.1
Heating oil	85-86	11-13	1-4	-	-	-	-
Natural gas	75	25	-	-	-	-	-

### 2.1.7.2 Ash content

The ash content can largely vary among biofuels. Normally, wood without bark has the lowest ash content, whereas agricultural biofuels typically have high ash content.

During combustion some physical modifications occur in the ashes; at a certain temperature, they soften until the complete fusion of the particle is reached creating fusion slags. Fusion slags disturb the combustion process by altering primary air flows and favouring the overheating of the grate as well as corrosive phenomena.

Wood and bark have relatively high melting point (1300-1400°C) and thus do not have any criticalities. On the contrary the melting point of herbaceous plants is below 1000°C and consequently slags can easily be created during combustion. In the case of cereal (grains) the melting point is lower than 750°C and is thus particularly critical.

**Table 2.9** Ash content in bark, wood chips, saw dust and straw (AEBIOM, 2009).

Elements	m.u.	Bark	Wood chips	Saw dust	Straw
pH	in CaCl <sub>2</sub>	12.7	12.8	12.5	11.2
CaO	wt% d.b.	42.2	44.7	35.5	7.4
SiO <sub>2</sub>		26.0	25.0	25.0	54.0
Al <sub>2</sub> O <sub>3</sub>		7.1	4.6	2.3	1.2
MgO		6.5	4.8	5.7	3.8
K <sub>2</sub> O		5.1	6.7	7.1	11.5
CO <sub>2</sub>		4	7.2	12.5	1
Fe <sub>2</sub> O <sub>3</sub>		3.5	2.3	3.7	1
P <sub>2</sub> O <sub>5</sub>		1.7	3.6	2.5	2.7
MnO		1.5	1.7	2.6	0.1
C <sub>org</sub>		0.8	1.3	5.9	5.2
Na <sub>2</sub> O		0.8	0.6	0.5	0.3
SO <sub>3</sub>		0.6	1.9	2.4	1.2
Zn		mg/kg <sub>d.b</sub>	618.6	375.7	1429.8
Cr	132.6		54.1	137.2	12.3
Ni	94.1		61.5	71.9	3.9
Cu	87.8		126.8	177.8	23.2
V	58.4		42.0	26.7	5.5
Pb	25.3		25.4	35.6	7.7
Co	23.9		15.3	16.7	1.5
As	11.4		8.2	7.8	5.4
Mo	4.8		1.7	3.4	7.1
Cd	3.9		4.8	16.8	0.7

For the reasons listed above, agricultural biofuels have higher criticalities as compared to wood and are only to be used in specific combustion devices.

Ash can be divided into two categories:

- bottom ash: it is a considerable portion of the ash that gathers under the boiler grate and it is channeled into a storage tank. It has a mass density of 1.3 t/m<sup>3</sup>;
- fly ash: it derives from flue gas cleaning and can further be divided into:
  - cyclone light ash;
  - fine particles from electrostatic and bag filters. It has a mass density of 0.8-0.9 kg/m<sup>3</sup>.

The components that most affect the environment (lead, cadmium and zinc) are those that are most volatile and predominantly gather in fine ash.

### 2.1.7.3 Calorific value and ashes

Another very important variable for combustion is the calorific value of a fuel because it expresses the amount of energy released during its complete combustion.

The calorific value depends on the moisture content, decreasing with the increasing of it, since part of the energy released during the combustion process is spent in water evaporation, which involves the consumption of 2.44MJ per kg of water, and is consequently not available for thermal use. The caloric value is defined as:

Net calorific value (NCV): amount of energy released during combustion minus the energy required to vaporize the water at 25°C.

Gross calorific value (GCV). amount of energy released during combustion before water vaporization. When not specified “calorific value” is to be intended as net calorific value.

The oven-dry calorific value (NCV<sub>0</sub>) of wood of different wood species varies within a very narrow interval, from 18.5 to 19 MJ/kg. In conifers it is 2% higher than in broad-leaved.

This difference is due especially to the higher lignin content – and partly also to the higher resin and oil content – present in conifers. Compared to cellulose (17.2-17.5 MJ/kg) an hemicelluloses (16 MJ/kg), lignin has a higher NCV<sub>0</sub> (26-27 MJ/kg). Some variability in the anhydrous calorific value is also due to the slight variability in hydrogen (H) content and to the comparatively much wider variability in ash contents.

However, when taking into account agricultural biofuels as well, the oven-dry calorific value varies within a 16.5 to 19 MJ/kg interval. The NCV<sub>0</sub> of wood fuels is on average 9% higher than that of herbaceous plant.

The net calorific value (MJ/kg) of wood can be evaluated from a given moisture content (M) through the following formula (Hartmann, 2007):

$$NCV_M = \frac{NCV_0 \cdot (100 - M) - 2.44 \cdot M}{100}$$

The net calorific value is a linear function of dry and wet basis moisture.

**Table 2.10** *Calorific values of wood in function of the moisture content (AEBIOM, 2009).*

<b>M(%)</b>	<b>kWh/kg</b>	<b>MJ/kg</b>
0	5.14	18.5
15	4.27	15.36
20	3.98	14.31
30	3.40	12.22
40	2.81	10.12
50	2.23	8.03
60	1.65	5.94

## **PART I**

### **Life Cycle Assessment of wood products for bioenergy**



## Chapter 3

### Life Cycle Assessment of wood products – Materials and methods

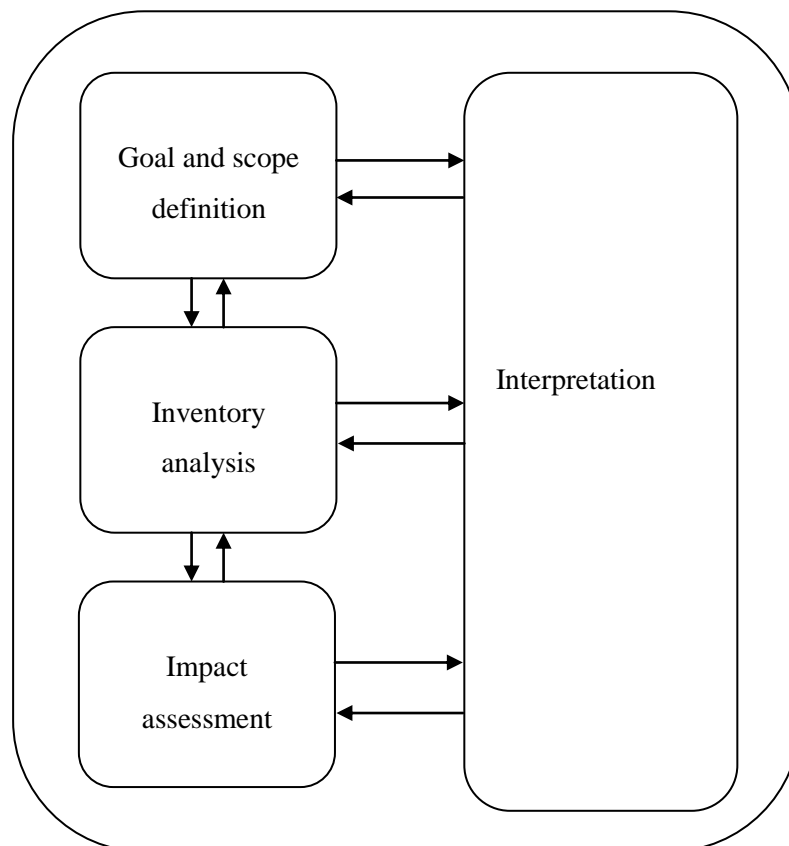
In this chapter the Life Cycle Assessment methodology will be presented.

#### 3.1 Life Cycle Assessment methodology

LCA is a protocol for assessing the environmental aspects and potential impacts associated with a product, process or activity. Based on the ISO 14040-44, the Life Cycle Assessment is defined as: “Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”.

As shown in Figure 3.1, LCA is constituted by the following four phases:

- Goal and scope definition
- Life cycle inventory analysis (LCI)
- Life cycle impact assessment (LCIA)
- Life cycle interpretation.



**Figure 3.1** Phases of the LCA (ISO 14040).

LCA is an iterative technique: as data and information are collected, various aspects of the scope may require modification in order to meet the original goal of the study.

### ***3.1.1 Goal and scope definition***

The goal and scope phase includes the definition of the system boundary and of the level of detail which depends on the subject and the intended use of the study.

The goal of an LCA states:

- the intended application, e.g. to make policy, to ensure compliance with law, to inform internal companies operations, to make marketing;
- the reasons for carrying out the study, e.g. comparing alternatives, identifying pollution prevention or resource conservation opportunities, planning for recycling;
- the intended audience, i.e. to whom the results of the study are intended to be communicated, and whether the results are intended to be used in comparative assertions intended to be disclosed to the public, e.g. inside or outside a company.

The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal.

The scope includes the following items:

- the product system object of study, e.g. wood product for buildings or biomass for energy; product systems are subdivided into a set of unit processes linked one to another by flows of intermediate products and/or waste for treatment, to other product systems by product flows, and to the environment by elementary flows;
- the function of the product system, e.g. if the product system is a wood product for buildings the function would be to be a “material”; if the product system is woody biomass the function would be to produce “energy”;
- the functional unit, defines the quantification of the identified functions (performance characteristics) of the product. It has to be defined based on the function of the product, e.g. if the function is “material”, the functional unit should be a mass (e.g. kg) or a volume (e.g. m<sup>3</sup>); if the function is “energy”, the functional unit should be a unit of energy, for example 1MJ. In the case of wood products, if it is possible to choice between mass and volume, it is recommended to use the volume since it varies less with the moisture content. A system may have a number of possible functions and the one(s) selected for a study depend(s) on the goal and scope of the LCA. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis. It is important to determine the reference flow in each product



system, in order to fulfil the intended function, i.e. the amount of products needed to fulfil the function;

- the system boundary: the system boundary defines the unit processes to be included in the system. The system boundary can be:
  - from “cradle to grave”: from the acquisition of the raw material from the environment until the end of life (e.g. combustion);
  - from “cradle to gate”: from the acquisition of raw material from the environment until the manufacture of the wood product;
  - from “gate to gate”: manufacturing processes only;
- allocation procedures: when processes yield more than one product or they recycle intermediate or discarded products as raw materials, an allocation procedures should be used to partition the input or output flows of a process or a product system between the product system under study and one or more other product systems;
- impact categories selected and methodology of impact assessment;
- interpretation to be used;
- data requirements;
- assumptions;
- limitations;
- initial data quality requirements: consistency, completeness, time related coverage, geographical coverage, technology coverage, precision, representativeness, reproducibility, uncertainty;
- type of critical review;
- type and format of the report required for the study.

### ***3.1.2 1.2 Life cycle inventory analysis (LCI)***

The life cycle inventory analysis is the phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle with regard to the system being studied. It involves collection of the data necessary to meet the goals of the defined study.

The data needed in LCA studies include:

- Activity data: they refer to the consumption of materials and energy for the different processes which constitute the life cycle of the product; they are expressed in, e.g. kg input/kg product; MJ input/kg product;
- Emission factors: emissions associated with the consumption of materials and energy for different processes; they are expressed in, e.g. kgCO<sub>2</sub>/kg input; kgCO<sub>2</sub>/MJ input.

### **3.1.3 Life cycle impact assessment (LCIA)**

The Life cycle impact assessment is the phase of life cycle assessment which aims to understand and evaluate the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

The purpose of LCIA is to provide additional information to help assessing a product system's LCI results so as to better understand their environmental significance.

The impact assessment phase of LCA aims to evaluate the significance of potential environmental impacts using the LCI results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. The LCIA phase also provides information for the life cycle interpretation phase.

Impact assessment includes :

- Classification: the emissions are attributed to the different impact categories to determine which environmental impacts they can potentially contribute to, e.g. CO<sub>2</sub> emissions will be attributed to the global warming category. Some emissions can be attributed to more than one impact category, e.g. methane emissions contribute to global warming as well as to the photochemical creation of ozone in the atmosphere (smog);
- Characterization: the potential environmental impacts are evaluated for the impact categories selected. They are evaluated by expressing the emissions of each chemical in terms of some reference substances, through some factors called characterization factors, e.g. for the global warming, the reference substance is CO<sub>2</sub> since it is the most common greenhouse gases in the atmosphere. The total impact is expressed in terms of emissions of the reference substance "equivalent", which means that the total impact of the different pollutants equals the impact of an equivalent amount of the reference substance.

Whereas inventory analysis can be seen as a model which includes all types of complications (cut-off, coproduct management, etc.) the characterization factors are simpler measures or metrics that are based on results from complex models, e.g.:

- fate and transport;
- exposure assessment;
- dose-response.

Facultative LCA phases are:

- Normalization: allow the impact category indicator results to be compared by a reference (or normal) value. This mean that the impact category is divided by reference impact indicators on the global, national, regional, or local level;
- Valuation/ Weighting: weighting across impact categories means the impact (or damage) category indicator results are multiplied by weighting factors, and are added to create a

total or single score. However subjective preferences are used to prioritize impact categories and impacts.

- Since the facultative phases introduce a certain level of subjectivity to the study, they should be used carefully accurately documenting the choices made.

Life cycle interpretation uses a systematic procedure to identify the conclusions of the LCA but there is no scientific basis for reducing LCA results to a single overall score or number, since weighting requires value choices.

Furthermore it is important to note that LCA addresses potential environmental impacts; LCA does not predict absolute or precise environmental impacts due to the inherent uncertainty in modeling of environmental impacts.

### ***3.1.4 1.4 Life cycle interpretation***

The Life cycle interpretation is the final phase of the LCA procedure in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated, summarized and discussed as a basis for decision-making in relation to the defined goal and scope.

The interpretation phase should reach conclusions, explain limitations and provide recommendations.

## **3.2 2. LCA computational model**

In this paragraph the LCA computational model is presented. The method is partially taken from (Heijungs and Suh, 2002) and partially from (Cooper, 2014).

The LCA inventory analysis can be modeled based on two levels of complexity:

- Simplified model: linear treatment of a steady-state situation.
- General model: accounts for non-linearities and dynamic situations.

### ***3.2.1 2.1 Simplified model for inventory analysis***

#### **3.2.1.1 Unit process**

A unit process can be represented by a vector, called process vector “p” containing all the inputs and outputs. A process vector represents the flow of good, materials, services, waste, substances, natural resources, land occupation, sound waves and other relevant items. Sign convention for the flows are:

- minus: input flow
- plus: output flow.

Column vectors are indicated as  $p_1$ ,  $p_2$  or  $p_j$  in general. An individual element of a process matrix

can be referred to as  $(P)_{ij}$  where  $i$  denotes the index of the row and  $j$  the index of the column.

### 3.2.1.2 System

The system of unit processes can be concisely represented by a matrix, called the process matrix “P”. Each column represent a unit process.

### 3.2.1.3 Partitioned matrix

The process matrix is then partitioned into two distinct parts:

- economic flows (product flows): flows within the economic system
- environmental flows or environmental interventions or interventions (elementary flows): flows from and into the environment

$$P = \begin{pmatrix} A \\ B \end{pmatrix}$$

P = partitioned matrix

A = technology matrix = matrix of economic flows

B = intervention matrix = matrix of environmental flows.

The number of columns of A and B is equal.

### 3.2.1.4 Specification of the required performance of the system.

How much of each process is needed for the reference flows (what is demanded from the system) is represented as a scaling vector “s”

$$s = A^{-1}f$$

f = final demand vector, i.e. how much of each economic flow is needed for the reference flows

A = technology matrix

s = scaling vector

The inventory model is a systematic construction of a set of linear balance equations with one economic flow and one scaling factor for each unit process.

The basic model presents matrix inversion as the means to solve the system, which requires a square and invertible non singular technology matrix.

The scaling vector  $s$  provides a direct clue to the final step in solving an inventory problem. The scaling of unit processes affect both economic and environmental flows and its solution allows to estimate the inventory vector  $g$ , which gives the life cycle amounts of each environmental flow:

$$g = Bs$$

The vector  $g$  is the solution of the inventory problem.

The basic model only applies when the number of processes equals the number of economic flows.

This is not automatically the case in:

- cut-off of economic flows
- multifunctional unit processes
- a choice between alternative processes
- closed loop recycling: a secondary material is fed back into a unit processes in the same system (closed loop recycling).

In those cases the general model should be applied.

### ***3.2.2 2.2 General model for inventory analysis***

For the detailed description of the general model reference is made to Heijungs and Suh, 2002. In this dissertation the aspects not covered in the linear model will be explained.

#### 3.2.2.1 Cut off economic flows

Cut off refers to incomplete systems (e.g., a certain material or component is used in a process but the upstream processes are not included in the system boundaries). There are three ways to solve this problem:

- estimate the missing information;
- add a “hollow process”, simply adding a column (a process) to the process matrix for every cut-off economic flow;
- remove the cut-off flows from the technology matrix, by further partitioning the technology matrix.

#### 3.2.2.2 Process alternatives

If a choice exists between alternative processes, an option is to keep separate the different processes by being more specific in the definition of processes and economic flows. If the process options are disaggregated it is possible to automatically analyze scenarios.

#### 3.2.2.3 Multifunctional processes

If a single process produces more than one valuable product or material (i.e. the process is multifunctional) there are several ways to solve the system:

- substitution method/system expansion: a separate avoided process for the production of the co-product is added to the system, although the choice of which avoided process to add

can be problematic (it can be multifunctional as well);

- surplus method: all burdens are allocated to the main flow and the co-products are ignored (not often used);
- partitioning method or allocation method. Allocation is the process of dividing the upstream environmental interventions of a unit process among products/co-products. It can be based on mass, energy, economic value.

ISO 14040 indicates that, whenever possible, allocation should be avoided by:

- collecting data for sub-processes;
- expanding the product system to include avoided processes.

Recently, these methods have been synthesized introducing the concepts of “attributional” and “consequential” LCAs (Ekvall, 2000; Ekvall and Weidema, 2004).

Attributional methodology for life cycle inventory analysis (LCI) aims at describing environmentally relevant physical flows to and from a life cycle and its subsystems.

In strict form, an attributional LCA model does not include unit processes other than those of the life cycle investigated and co-products are all allocated

Contrarily, consequential LCA methodology aims at describing how the environmentally relevant physical flows to and from the technosphere will change in response to possible changes made within the life cycle. A consequential LCI model includes unit processes that are significantly affected irrespective of whether they are within or outside the life cycle.

Thus the methods to solve a multifunctional problem have been synthesized by:

- using allocation in attributional LCAs
- avoid allocation in consequential LCAs by means of system expansion. A consequential LCI model can also include economic partial equilibrium models and other tools designed to quantify specific causal relationships

#### 3.2.2.4 Closed loop recycling

When a secondary material is fed back into a unit processes in the same system (closed loop recycling), thus displacing the use of virgin materials, flows for the secondary material are a part of the product system and there is no need to allocate their burden elsewhere nor expand the system. In this case, instead of treat it as a co-product a pseudo-inverse matrix can be used in place of the matrix inverse:

$$s = (A^T A)^{-1} A^T f$$

$$A^+ = (A^T A)^{-1} A^T$$

$$s = A^+ f$$

or

$$s = (A^T A)^{-1} A^T f$$

Since the pseudo-inverse essentially performs a least-squares regression to minimize the discrepancy vector,  $A*s$  will not exactly equal  $f$  unless all of the material (and no more) is used by the process that recycles it.

### 3.3 3. LCA databases

The hierarchy of the inventory data is:

- Primary data: data directly collected on the site object of study; if it possible to collect primary data, this should be the first choice;
- Secondary data: data collected from other sources like journals, technical papers, manuals, industrial reports, databases. These data should be used only if primary data were not available or was not possible to produce them.

The main LCA database are described in Table 3.1.

An important distinction regards unit data and aggregated data:

- Unit data are LCI data available for each unit process of the product system;
- Aggregated data are often presented from cradle-to-the point of use, combining unit processes, usually representing all upstream processes. In aggregated data most of the flows are elementary, this it is not possible to separate the LCI of a single unit from the total.

**Table 3.1** *Description of the main LCA database.*

<b>Name</b>	<b>Country</b>	<b>Description</b>
USDA LCA Data Commons	United States	It provides data for use in LCAs of food, bio-fuels, and a variety of other bio-products. Current data cover US field crop production (corn, cotton, oats, peanuts, rice, soybeans, and durum, other spring, and winter wheat in USDA Program States from 1996-2009). It also includes unit process data representing mineral and organic fertilizer production; herbicide, insecticide, and fungicide production; crop storage; transport. Irrigation, manure management, and farm equipment operation unit process data are in peer review or under development. Access at <a href="http://www.lcacommons.gov">http://www.lcacommons.gov</a>
U.S. Life-Cycle Inventory (LCI) Database	United States	Created by the US Department of Energy National Renewable Energy Laboratory and its partners, the database provides a cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly. It's an online store room of data collected on commonly used materials, products, and processes. Access at <a href="http://www.nrel.gov/lci/">http://www.nrel.gov/lci/</a> A database roadmap is at <a href="http://www.nrel.gov/lci/pdfs/45153.pdf">http://www.nrel.gov/lci/pdfs/45153.pdf</a> The National Energy Technology Laboratory Unit Process Library includes datasets representing various aspects of the energy production life cycles for coal, biomass, natural gas, nuclear, hydroelectric, wind, geothermal, and solar systems. Each NETL unit process contains a DS and DF file. The DS file (Detailed Spreadsheet Documentation) is an Excel file that contains all of the parameters, inputs, and outputs for a given system as well as background data, calculations and quality scores. The DF file (Process Documentation File) is a PDF document that contains major assumptions and data sources that are the basis for each unit process. Access at <a href="http://netldev.netl.doe.gov/research/energy-analysis/life-cycle-analysis/unit-process-library">http://netldev.netl.doe.gov/research/energy-analysis/life-cycle-analysis/unit-process-library</a>
Gate-to-Gate Life Cycle Inventory Data (Wichita State)	United States	It contains life cycle inventory data on several materials used in wind turbine manufacturing (i.e., related to the life cycles of aluminum, carbon fiber reinforced epoxy, glass fiber reinforced plastic, and steel). Unit process data are provided in pdf format. Access at <a href="http://cratel.wichita.edu/gtglci/">http://cratel.wichita.edu/gtglci/</a>
Manufacturing Unit Process Life Cycle Inventory Heuristics (Wichita State)	United States	It contains raw data and formulas (as heuristics) that can be used to develop transformation unit process data. A life cycle heuristic is to establish representative estimates of the energy and mass loss from a unit process in the context of efficient manufacturing operations for products. The unit process life cycle inventory (UPLCI) profile is for a high production manufacturing operation, defined as the use of processes that generally have high automation. Access at <a href="http://cratel.wichita.edu/uplci/">http://cratel.wichita.edu/uplci/</a>
Canadian Raw Materials Database	Canada	It involves a cross-section of Canadian materials industries to develop a database profiling the environmental inputs and outputs associated with the production of Canadian commodity materials. Industry associations are participating on a voluntary basis with Environment Canada as chair. Materials industries participating are: aluminum, glass, plastics, steel and wood. The database methodology was developed, completed and published by the Canadian Standards Association as CSA PLUS 1116. Data collection by each of the five active industry groups using the methodology was completed in early 1998 and subsequently submitted for critical review. A Critical Review Report was submitted to Environment Canada in November 2000. Access at <a href="http://crmd.uwaterloo.ca/">http://crmd.uwaterloo.ca/</a>
The European Union's European Reference Life Cycle Data System ELCD	European Union	The database comprises - next to other sources - LCI data sets of the European Confederation of Iron and Steel Industries (EUROFER), The Association of Plastics Manufacturers in Europe (PlasticsEurope, former APME), The European Federation of Corrugated Board Manufacturers (FEFCO), Groupement Ondulé (GO), and the European Container Board Organisation (ECO). The data sets to be provided by the European Aluminium Association (EAA) and the European Copper Institute (ECI) were also added to the ELCD



database in August 2006. All these data sets are officially provided and approved by the named association for publication in the Commission's ELCD core database. This database is available online for free, but most of its data is aggregated.

Access at <http://lca.jrc.ec.europa.eu/lcainfohub/datasetCategories.vm>

Swiss National LCI Database EcoInvent	Switzerland	<p>The Swiss Centre for Life Cycle Inventories was founded in 2000 and currently includes institutes and departments of the Swiss Federal Institutes of Technology Zürich (ETHZ) and Lausanne (EPFL), of the Paul Scherrer Institute (PSI), Villigen, of the Swiss Federal Laboratories for Materials Testing and Research (Empa), and of the Swiss Federal Research Station for Agroecology and Agriculture (Agroscope FAL Reckenholz). The Swiss Centre for Life Cycle Inventories funded the development and programming of the ecoinvent database and its current operation. Its members were in charge with LCI data compilation and updating within the project ecoinvent 2000. The ecoinvent data contain harmonised generic LCA data covering over 10,000 processes in the following sectors: energy, transport, waste treatment, buildings, chemicals, detergents, graphical papers and agriculture. The geographic scope comprises the supply situation in Switzerland and in Western Europe.</p> <p>The system includes a query tool: used by third parties for a user-friendly access to the ecoinvent database via a web-browser. It enables simple and advanced searches as well as the download of datasets.</p> <p>Data exchange is based on the EcoSpold data format, which is written in XML.</p> <p>Access at <a href="http://www.ecoinvent.ch/">http://www.ecoinvent.ch/</a></p>
LCA-National Project in Japan	Japan	<p>Funded by the Ministry of Economy, Trade and Industry (METI), since 1998 it has been completed at the end of March 2003. It includes (1) LCA methodologies, especially the LCIA method and the practical LCI method for recycling, (2) LCA database for Japan and (3) a network system to show the results of (1) and (2). The LCI data for approximately 200 products were collected based on the sub-system, i.e. from gate to gate, by 22 industrial associations joined to the project officially, and by around 30 industrial associations contributed to the project unofficially. The inventory data such as resource exploitation and oversea transportation were prepared by the survey of the literatures.</p> <p>Access at <a href="http://lcacenter.org/InLCA-LCM03/Narita-abstract.pdf">http://lcacenter.org/InLCA-LCM03/Narita-abstract.pdf</a></p>
Australian LCA Network	Australia	<p>It is the portal for Australian life cycle inventory (LCI) and life cycle assessment (LCA) information. Methodologies, guidelines and protocols developed by AusLCI for collection and quality of data are available for download, along with specific sector product LCI datasets. Data sets cover plastics and electricity.</p> <p>Access at <a href="http://www.auslci.com.au/">http://www.auslci.com.au/</a></p>
LCA Food Database-Denmark	Denmark	<p>It is a result of the project "Lifecycle Assessment of Basic Food" (2000 to 2003) by the Danish Institute of Agricultural Sciences, Danish Institute for Fisheries Research, Højmarkslaboratoriet, Danish Research Institute of Food Economics, Danish Technological Institute, and 2.-0 LCA Consultants. The site is hosted by Danish Institute of Agricultural Sciences. Data are also available in the LCA tool SimaPro. Text in process data sheets is arranged with bookmarks following the nomenclature of ISO/TS 14048 and data can be exported automatically to databases applying the ISO format.</p> <p>Access: <a href="http://www.lcafood.dk/lcamodel.htm">http://www.lcafood.dk/lcamodel.htm</a></p>
Swedish National LCA database (CPM)	Sweden	<p>The CPM LCA Database is a result of the continuous work within CPM to establish transparent and quality reviewed LCA data. It contains LCI datasets and LCIA models based on the SPINE data format.</p> <p>Access at <a href="http://cpmdatabase.cpm.chalmers.se/Start.asp">http://cpmdatabase.cpm.chalmers.se/Start.asp</a></p>
Korea National LCI Database	Korea	<p>Korea National Cleaner Production Center (KNPC) constructed an LCI database for Korean industries with the support of Ministry of Commerce Industry and Energy. The database is based on the request from industries through series of surveys and it is accessible through KNPC website.</p> <p>Access at <a href="http://www.knpc.re.kr/eng/topics/Lci.asp">http://www.knpc.re.kr/eng/topics/Lci.asp</a></p>

### **3.4 4.LCA Softwaress**

Many LCA softwares exist, including GREET, SimaPro, Gabi, Quantis Suite, EarthSmart, Sustainable Minds, Enviance System, LinkCycle Footprinter, Gemis, Tremove, Umberto. The most popular software: GREET, SimaPro and Gabi will be described below.

#### ***3.4.1 4.1 Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) Model***

Sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), Argonne National lab has developed a full life-cycle model to fully evaluate energy and emission impacts of advanced vehicle technologies and new transportation fuels. GREET allow researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle cycle basis. For a given vehicle and fuel system, GREET separately calculates:

- Consumption of total energy (energy in non-renewable and renewable sources), fossil fuels (petroleum, natural gas, and coal together), petroleum, coal and natural gas.
- Emissions of CO<sub>2</sub>-equivalent greenhouse gases - primarily carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O).
- Emissions of six criteria pollutants: non-methane volatile organic compounds (NMVOCs OR VOCs), carbon monoxide (CO), nitrogen oxide (NO<sub>x</sub>), particulate matter with size smaller than 10 micron (PM<sub>10</sub>), particulate matter with size smaller than 2.5 micron (PM<sub>2.5</sub>),and sulfur oxides (SO<sub>x</sub>).

Although GREET applications to date are primarily assessments of mobile systems (assessments of aircraft, marine transport and personal vehicles including fuel cell vehicles), what is often of value are the fuel cycle, electricity production, logistics models (transport on land, through inland waters, or by sea), and materials production models contained within GREET.

These include, but are not limited to, life cycle scenarios for U.S. production of several fuels used by emerging generation technologies (e.g., hydrogen, biomass, etc.). Further, because energy production, logistics, and refinery processes are part of the GREET fuel cycle model, these data (including refinery co-products) can be used for the preparation of LCAs for industrial activities throughout the technology system life cycle.

So, GREET has some data for many types of LCAs, but tracks far fewer interventions than the USDB. Comparing the USDB and GREET databases for fuels, and electricity generation, and transport mode, based on version 1.8a of GREET they compare pretty well except for biomass to electricity. Since the USDB process is aggregated, it is not possible to separate the LCI components, but the difference could be in the method used to account sequestration and soil processes.

### 3.4.2 4.2 SimaPro software

Developed by PRé Consultants, a company located in Netherlands, SimaPro is one of the leading LCA software, being used by industry, consultancies, universities and research institutes in more than 80 countries. SimaPro provides a professional tool to collect, analyze and monitor the sustainability performance of products and services. The last version of the software, SimaPro v.8, includes many updated LCI datasets, including the renewed ecoinvent v3 database, the new industry-specific Agri-footprint database and the ELCD database. Input Output databases and the U.S. Life Cycle Inventory Database (USLCI) are also present. Modeling in SimaPro consists in the creation of processes containing input and output flows connected to each other to form a network or a tree structure. SimaPro interface is shown in Figure 3.2.

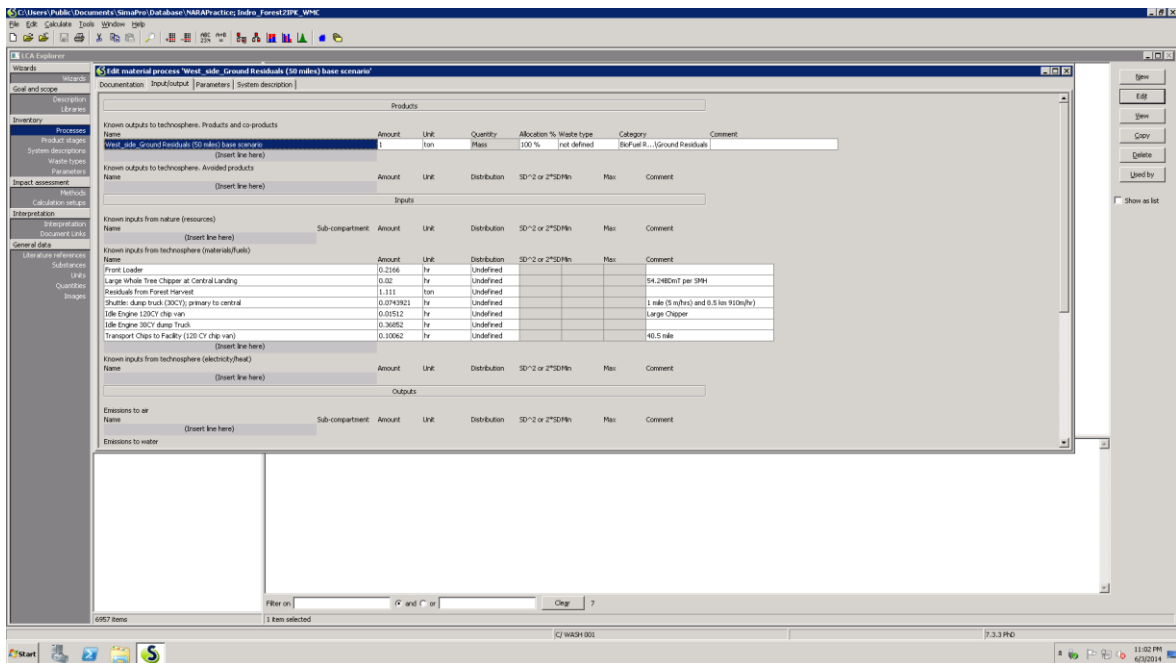


Figure 3.2 Screenshot of the SimaPro v.8 interface.

### 3.4.3 4.3 Gabi software

Gabi software was created by PE International and is one of the most trusted product sustainability tool for Life Cycle Assessment with over 10,000 users including 500 companies, leading industry associations and innovative SMEs. As opposed to SimaPro, besides the others, Gabi contains a database created by PE International containing over 7,000 LCIs. Furthermore the interface is different since the product system is modeled through a system of flows, processes and plans connected to each other in a hierarchic way. A picture of Gabi's interface is shown in Figure...

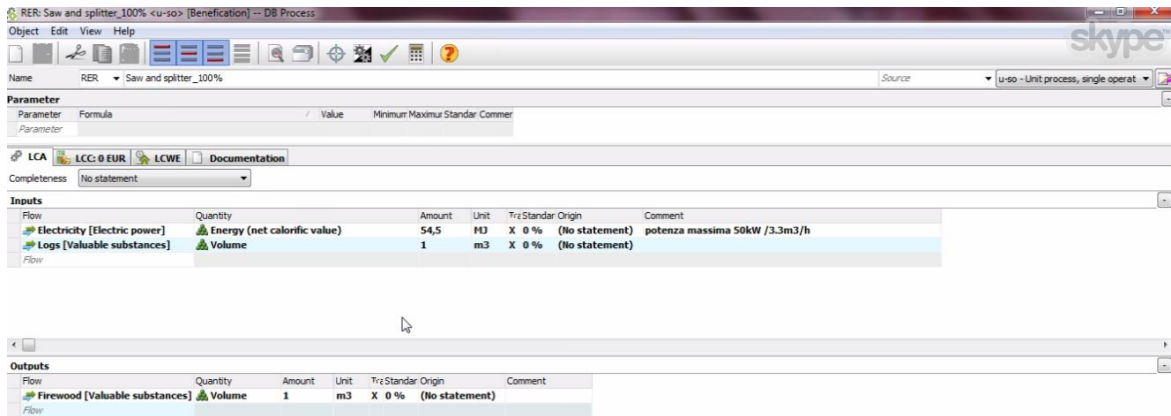


Figure 3.3 Screenshot of Gabi v.5 interface.

### 3.5.5. Impact assessment methods

The most common impact assessment methods included in LCA softwares are described below. Those methods are available in both SimaPro and Gabi softwares. Some of them focus on environmental impacts, others consider other aspects of sustainability, i.e. social and economic aspects (PRé Consultants, 2014).

They differ for the number and types of impact categories, the models and the origin of the data used to develop the characterization factors, the use of normalization and weighting factors.

In LCA impact categories are classified at:

- midpoint level: it is a “problem oriented” approach and includes specific impact categories for each environmental issue, such as global warming, ozone depletion, eutrophication, etc;
- endpoint level: it is a “damage oriented” approach” aiming to synthesize the impacts into bigger categories, such as ecosystem quality, human health, etc.

If impact categories are defined at midpoint level, the higher number of impact categories makes the drawing of conclusions more complex compared to endpoint level, which makes the interpretation of the results easier. The main impact assessment methods used in LCA softwares are briefly described below.

#### 3.5.1 CML-IA

Developed in 2001 by a group of scientist of the Center of Environmental Science of Leiden University (CML), the current version has been updated in 2013. The impact assessment method implemented as CML-IA methodology is defined for the midpoint approach. Normalization is provided but there is neither weighting nor addition. CML contains obligatory and additional impact assessment categories.

### **3.5.2 Ecological scarcity 2013**

It is a Swiss method called Ecopoints 97 in the SimaPro method library. The Ecological scarcity method weights environmental impacts - pollutant emissions and resource consumption - by applying "eco-factors" derived from characterization, normalization and weighting. The eco-factor of a substance is derived from environmental law or corresponding political targets, expressed in eco-points (EP = UBP). Weighting is conducted on the basis of goals set by Swiss environmental policy. In specific cases, global, international or regional goals are used and converted to the Swiss level. The method can also be applied to other countries and regions. To do so, information about the current environmental situation and the official environmental targets is required.

### **3.5.3 EDIP 2003**

EDIP 2003 is a Danish LCA methodology which updates the EDIP 97 methodology. The EDIP 2003 methodology represents 19 different impact categories. The main innovation of EDIP2003 lies in the consistent attempt to include exposure in the characterization modelling of the main non-global impact categories. There are normalization factors provided for Europe in the reference year 2004.

### **3.5.4 EPD (2013)**

This method is the successor of EPD (2008) and is to be used for the creation of Environmental Product Declarations (EPDs), as published on the website of the Swedish Environmental Management Council (SEMC). This method is especially important for everybody who is reporting a Product Category Rule (PCR) published by Environdec. In the standard EPDs only the following impact categories have to be reported: global warming, photochemical oxidant creation, acidification and eutrophication potentials. Contrarily, the impact categories ozone depletion and abiotic resource depletion are optional and their inclusion should be specified in the PCR. The method does not include normalization and weighting.

### **3.5.5 EPS 2000**

The EPC (Environmental Priority Strategies in product design) method is a damage oriented method. In the EPS system, willingness to pay to restore changes in the safe guard subjects is chosen as the monetary measurement. The indicator unit is ELU (Environmental Load Unit), which includes characterization, normalization and weighting.

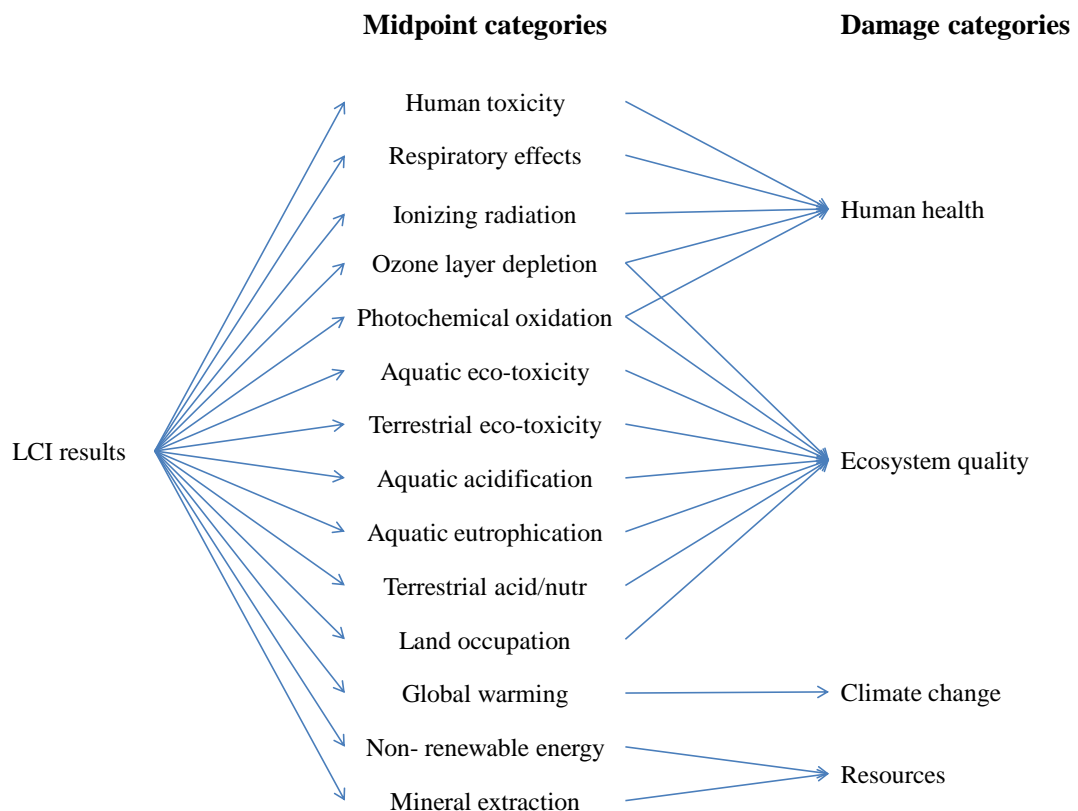
The EPS system is mainly aimed to be a tool for a company's internal product development process. The system is developed to assist designers and product developers in finding which one of two product concepts has the least impact on the environment.

The EPS 2000 default method is an update of the 1996 version. The impact categories are identified from five safe guard subjects: human health, ecosystem production capacity, abiotic stock resource, biodiversity and cultural and recreational values.

This method is not fully adapted for inventory data from the Ecoinvent library and the USA Input Output Database 98, and therefore omits emissions that could have been included in impact assessment. Empirical, equivalency and mechanistic models are used to calculate default characterization values. In the EPS default method, normalization/weighting is made through valuation. Normalization/weighting factors represent the willingness to pay to avoid changes.

### 3.5.6 Impact 2002+

The Impact 2002+ (Impact Assessment of Chemical Toxics) is an impact assessment methodology originally developed at the Swiss Federal Institute of Technology - Lausanne (EPFL), with current developments carried out by the same team of researchers now under the name of Ecoinventsys-life cycle systems (Lausanne).



**Figure 3.4** Scheme of the Impact 2002+ LCA evaluation method (*PRé Consultants, 2014*).

The methodology proposes an implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results via 14 midpoint categories to four damage categories, as shown in Figure. In SimaPro only the characterization factors at endpoint level are provided.

The characterization factors for human toxicity and aquatic and terrestrial ecotoxicity are taken from the methodology IMPACT 2002+. The characterization factors for other categories are adapted from existing characterizing methods, i.e. Eco-indicator 99, CML 2001, IPCC and the Cumulative Energy Demand. The IMPACT 2002+ method (version 2.1) presently provides characterization factors for almost 1500 different LCI-results. In SimaPro, 15 different impact categories are presented, as human toxicity is split up in ‘Carcinogens’ and ‘Non-carcinogens’. Normalization factors are provided. The authors of IMPACT2002+ suggest to analyze normalized scores at damage level considering the four-damage oriented impact categories or, alternatively, the 14 midpoint indicators separately for the interpretation phase of LCA.

### ***3.5.7 ReCiPe***

ReCiPe is the successor of the methods Eco-indicator 99 and CML-IA. The purpose at the start of the development was to integrate the ‘problem oriented approach’ of CML-IA, which defines the impact categories at a midpoint level and the ‘damage oriented approach’ of Eco-indicator 99 which results in only three impact categories.

ReCiPe implements both strategies including both midpoint and endpoint impact categories. At the midpoint level 18 impact categories are addressed, at the endpoint level, most of these midpoint impact categories are multiplied by damage factors into three endpoint categories:

1. Human health: expressed as the number of year life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs), an index that is also used by the World Bank and WHO.
2. Ecosystems: expressed as the loss of species over a certain area, during a certain time.
3. Resource surplus costs: expressed as the surplus costs of future resource production over an infinite timeframe (assuming constant annual production), considering a 3% discount rate.

The three endpoint categories are normalized, weighted, and aggregated into a single score. The normalization is recalculated per citizen based on the report of (Sleeswijk et al., 2008). The used population of EU25+3 is 464,036,294 citizens and of the world 6,055,000,000 citizens. Weighting is performed at damage category level (endpoint level).

### ***3.5.8 ILCD 2011 Midpoint+***

This is the corrected and updated method of the ILCD 2011 Midpoint (without the +). The European Commission (EC-JRC–IES, 2011) analyzed several methodologies for LCIA and made some effort towards harmonization. Starting from the first pre-selection of existing methods and the definition of criteria, a list of recommended methods for each impact category at both midpoint and endpoint was produced. The normalization factors were added as provided in (European

Commission, 2014). Weighting factors were added with equal weights for each of the recommended categories as indicated by the guidance document.

### **3.5.9 BEES**

The Building for Environmental and Economic Sustainability (BEES) is a software tool developed by the National Institute of Standards and Technology (NIST). BEES is based on consensus standards and designed to be practical for application by designers, builders, and product manufacturers. It combines a partial life cycle assessment and life cycle cost for hundreds of building and construction materials into one tool.

BEES uses the SETAC method of classification and characterization.

Normalization is implemented as described in the report (Lippiatt, 2007) and weighting as described in (Gloria et al., 2007).

### **3.5.10 TRACI 2.1**

The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) is a computer program developed by the U.S. Environmental Protection Agency specifically for the US. Input parameters consistent with US locations are used and site specificity is available for many of the impact categories. When the location is undetermined, in all cases a US average value exists.

TRACI is a midpoint oriented life cycle impact assessment methodology, consistently with EPA's decision not to aggregate between environmental impact categories. It includes classification, characterization and normalization.

Morten Rybert from the Technical University of Denmark calculated normalization factors for the US and US + Canada. Data from 2008 and 2005 combined with 2008 were used for these reference geographies, respectively.

## **3.6 6. Impact categories overview**

Table 3.2 summarizes the impact categories used in the LCA methods analyzed above.

If read horizontally, the table allows the comparison between the methods to know where each impact category is included. Impact categories are highlighted with bold lines; it can be observed that for some categories there is heterogeneity in the names and groups used to refer to the same quantity. If read vertically, the table shows the total number of impact categories evaluated for each method.



**Table 3.2 Comparison of the impact categories included in LCA methods.**

CML-IA	ECOLOG. SCARCITY	EDIP 2013	EPD (2013)	EPS 2000	IMPACT 2002+	RECIPE	ILCD 2011 MIDPOINT	BEEES	TRACI 2.1
Climate change	Global warming	Global warming	Global warming	-	Global Warming	Climate change	Climate change	Global warming	Global warming
Stratospheric ozone depletion	Ozone layer depletion	Ozone depletion	Ozone depleting OPTIONAL	-	Ozone layer depletion	Oxone depletion	Ozone depletion	Ozone depletion	Ozone depletion
Human toxicity	Carcinogenic substances into air	Human toxicity (exposure via air)	-	Human health	Human toxicity	Human toxicity	Human toxicity, cancer effect	Human health	Carcinogenics
-	Main air pollutants and PM	Human toxicity (exposure via water)	-	-	Respiratory effects	Particulate matter formation	Human toxicity, non cancer effect	-	Non carcinogenics
-	Heavy metals into air	Human toxicity (exposure via soil)	-	-	-	-	Particulate matter/ respiratory inorganics	Criteria air pollutants	Respiratory effects
-	Heavy metals into water	-	-	-	-	-	-	In door air quality	-
-	Pesticides into soil	-	-	-	-	-	-	-	-
-	Heavy metals into soil	-	-	-	-	-	-	-	-
Acidification	-	Acidification	Acidification	-	Aquatic acidification	Terrestrial acidification	Acidification	Acidific.	Acidification
-	-	-	-	-	Terrestrial acid/nutr	-	-	-	-
Eutrophication	-	Terrestrial eutrophication	Eutrophication Potential	-	Aquatic eutrophication	Marine eutrophication	Eutrophication, terrestrial	Eutrophic.	Eutrophication
-	-	Aquatic eutrophication (N-eq)	-	-	-	Fresh water eutrophic.	Eutrophication, aquatic	-	-
-	-	Aquatic eutrophication (P-eq)	-	-	-	-	-	-	-
Fresh-water aquatic ecotoxicity	Water pollutants	Ecotoxicity (water acute)	-	-	Terrestrial ecotoxicity	Terrestrial ecotoxicity	Ecotoxicity (freshwater)	Ecological toxicity	Ecotoxicity
Marine ecotoxicity	POP into water	Ecotoxicity (water chronic)	-	-	Aquatic ecotoxicity	Marine ecotoxicity	Ecotoxicity (terrestrial and marine)	-	-
Terrestrial ecotoxicity	Heavy metals into water	Ecotoxicity (soil chronic)	-	-	-	Fresh water ecotoxicity	-	-	-
Photo-oxidant formation	-	Ozone formation (human)	Photochemical oxidant creation potential	-	Photochemical oxidation	Photochemical oxidant formation	-	Smog	-
-	-	Ozone formation (vegetation)	-	-	-	-	-	-	-
-	Land use	-	-	-	Land occupation	Agricultural and urban land occupation	Land use	-	-
-	-	-	-	-	-	Natural land transformation	-	-	-
Depletion of abiotic resources	Water sources	Resources	Abiotic resource depletion OPTIONAL	Abiotic stock resources	-	Fresh water depletion	Resource depletion, water	Water intake	Fossil fuel depletion
-	Energy sources	-	-	-	Non-renewable Energy	Fossil fuel depletion	Resource depletion, mineral, fossil and renewable	Fossil fuel depletion	-
-	-	-	-	-	Mineral extraction	Minerals depletion	-	-	-
-	-	-	-	Ecosyst. product. capacity	-	-	-	Habitat alteration	-
-	-	-	-	Biodiver.	-	-	-	-	-
-	-	-	-	Cultural and recr. values	-	-	-	-	-
-	Radioactive substances into air	Slags/ ashes	-	-	Ionizing radiation	Ionizing radiation	-	-	-
-	Radioactive substances into water	-	-	-	-	-	-	-	-
-	Non radioactive waste to deposit	-	-	-	-	-	-	-	-
-	Radioactive waste to deposit	Radioactive waste	-	-	-	-	-	-	-
-	Deposited waste	Bulk waste	-	-	-	-	-	-	-
-	-	Hazardous waste	-	-	-	-	-	-	-
-	Noise	-	-	-	-	-	-	-	-

### ***3.6.1 Climate change***

Climate change is the phenomenon of increase of the average global temperature related to emissions of greenhouse gases to air. The characterization factors selected are those developed by the Intergovernmental Panel on Climate Change (IPCC) for time horizon 100 years (GWP100). The impact is expressed in terms of equivalent carbon dioxide and the geographic scope of this indicator is global scale. Climate change is included in all the evaluation methods except for the EPS 2000, since it is an endpoint approach only.

In the Ecological scarcity method the distance to target principle is applied. For climate change a reduction target of 80% has been set for CO<sub>2</sub> and other greenhouse gases. This falls in the upper range of the Swiss reduction target and within the range of the reduction required to achieve the 2°C target.

### ***3.6.2 Stratospheric Ozone depletion***

The stratospheric ozone depletion refers to the reduction of the ozone layer in the stratosphere which protects the earth surface from the UV-B radiation. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. This category is output-related and at global scale. The characterization model is developed by the World Meteorological Organization (WMO) and defines ozone depletion potential of different gases in terms of kg CFC-11 eq/kg emission. Like climate change, stratospheric ozone depletion is included in all the evaluation methods except for the EPS 2000 although for the EPD (2013) its evaluation is facultative.

### ***3.6.3 Human toxicity***

This category concerns effects of toxic substances on the human environment. The human toxicity category is included in all the LCA methods, except for EPD (2013). Based on the CML method, the Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. In CML and ReCiPe methods, for each toxic substance HTP's are expressed as 1,4-dichlorobenzene equivalents/kg emission. The geographic scope of this indicator determines on the fate of a substance and can vary between local and global scale.

In the EDIP 2013 characterization factors for human toxicity, exposure route via air, are enhanced. The new exposure factors are established for:

- Two different kinds of substances: short-living (hydrogen chloride) and long-living (benzene);
- Actual variation in regional and local population densities: added for each substance;

- Different release heights: 1m, 25m and 100m with the release height of 25m presented as default.

In the EPS method weighting factors for damage to human health include life expectancy, morbidity and severe morbidity, nuisance and severe nuisance.

In ReCiPe the characterization factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical.

### ***3.6.4 Acidification***

Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification Potential (AP) for emissions to air is calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as kg SO<sub>2</sub> equivalents/ kg emission; the time span is eternity and the geographical scale varies between local scale and continental scale.

### ***3.6.5 Eutrophication***

Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential (NP) is based on the stoichiometric procedure of (Heijungs et al., 1992), and expressed as kg PO<sub>4</sub> equivalents per kg emission. Fate and exposure is not included, time span is eternity, and the geographical scale varies between local and continental scale

In EDIP 2003, characterization factors for aquatic eutrophication are developed for two impact categories: aquatic eutrophication (N-eq) and aquatic eutrophication (P-eq). This double set of characterization factors reflects the fact that, in general, eutrophication is limited by nitrate in fresh waters, and phosphate in marine waters. In each impact category, characterization factors for emissions effecting fresh waters and emissions effecting marine waters are developed.

The same approach is used in ReCiPe where eutrophication is split in two different types: the marine and the freshwater eutrophication. The characterization factor of marine eutrophication and freshwater eutrophication account for the environmental persistence (fate) of the emission of N and of P containing nutrients respectively.

### ***3.6.6 Eco-toxicity***

The Eco-toxicity impact category includes the following subcategories;

- Fresh-water human toxicity: it refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. Eco-toxicity Potential (FAETP) are

calculated with USES-LCA, describing fate, exposure and effects of toxic substances. The time horizon is infinite. Characterization factors are expressed as 1,4-dichlorobenzene equivalents/kg emission. The indicator applies at global/continental/ regional and local scale.

- Marine eco-toxicity: it refers to impacts of toxic substances on marine ecosystems (see description fresh water toxicity);
- Terrestrial eco-toxicity: it refers to impacts of toxic substances on terrestrial ecosystems (see description fresh water toxicity).

### ***3.6.7 Photochemical Ozone Creation Potential (POCP)***

Photo-oxidant formation is the formation of reactive substances (mainly ozone) in the troposphere which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with “smog”. Photochemical Ozone Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg emission. The time span is 5 days and the geographical scale varies between local and continental scale.

In ReCiPe the characterization factor of photochemical oxidant formation is defined as the marginal change in the 24h-average European concentration of ozone due to a marginal change in emission of substance  $x$  and it is measured in kg NMVOC.

### ***3.6.8 Land use***

The agricultural and urban land occupation refers to the amount of either agricultural land or urban land occupied for a certain time. Due to the uncertainty in the estimation of this impact category, only a few methods include it in the evaluation, i.e. ecological scarcity, Impact 2002+, ReCiPe and ILCD. The impact is expressed in terms of  $m^2$ yr.

### ***3.6.9 Depletion of abiotic resources***

This impact category regards the protection of human welfare, human health and ecosystem health. It is related to the extraction of minerals and fossil fuels due to inputs in the system and it is evaluated by all the reviewed methods. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation. The geographic scope of this indicator is at global scale. In this group the “abiotic stock resources” from EPS 2000 has been included. Abiotic stock resource indicators are depletion of elemental or mineral reserves and depletion of fossil reserves. In ReCiPe depletion is considered for fossil fuel, minerals and freshwater. The

characterization factor of fossil depletion is the amount of extracted fossil fuel extracted, based on the lower heating value, expressed in kg oil equivalent (1 kg of oil equivalent has a lower heating value of 42 MJ). The characterization factor for minerals depletion is the decrease in grade, expressed in kg Iron (Fe) equivalents. The factor for the freshwater depletion is the amount of fresh water consumption, expressed in m<sup>3</sup>.

#### ***3.6.10 Habitat and ecosystems***

In this group the impact categories “ecosystem production capacity”, “biodiversity” and “cultural and recreational values” from the EPS 2002 have been included. The “ecosystem production capacity” includes crop, wood, fish and meat production capacity, base cation capacity, irrigation and drinking water capacity. The “biodiversity” category regards the extinction of species, expressed in Normalized Extinction of species (NEX). The “cultural and recreational values” regards changes in recreational habits. They are difficult to describe by general indicators as they are highly specific and qualitative in nature, thus indicators are not included in the default methodology.

#### ***3.6.11 Ionizing radiation***

In ReCiPe the characterization factor of ionizing radiation accounts for the level of exposure. The unit is yr/kg Uranium 235 equivalents.



## Chapter 4

### Life Cycle Assessment of firewood for domestic heating

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#### 4.1 Abstract

This work aims to evaluate the environmental impacts of the firewood supply chain from high stand beech forest in North-Eastern Italy. Two scenarios have been considered: the first scenario investigates the firewood supply chain based on the wood harvested from the local forest, while the second one investigates the supply chain based on wood imported from the Balkans' area.

The differences between the two scenarios are assessed through a “cradle to grave” Life Cycle Assessment for the impact categories: Global Warming Potential (GWP) and Ozone Depletion Potential (ODP); Photochemical Ozone Creation Potential (POCP) and Human Toxicity Potential (HTP). The functional unit is 1 MJ of energy produced by firewood.

The study has shown that there are different critical values of transportation distance for impact categories.

Although most of the chemicals emitted in the life cycle of firewood cannot be offset, a sustainable forest management can completely offset the fossil CO<sub>2</sub> emissions of the short and the long supply chain by saving less than 10% of the net increment.

#### 4.2 Introduction

A large portion of the harvested wood in Italy is used for the production of firewood that is primarily burned for domestic heating. A survey conducted by APAT-ARPA shows that 25.6% of the Italian families uses firewood for domestic heating, percentage which increases to 38.7% for the families living in the mountain areas (APAT and ARPA, 2008). According to the Istat/Eurostat data, the wood harvested in Italy for energy purpose reached 70% of the total harvested wood in 2011, considerably higher if compared to the share below 50% recorded in the seventies (Pettenella et al., 2013). Based on the National Action Plan for the Renewable Energy, the total solid biomass, the main component of which is woody biomass, should cover the 8% of the electricity production and the 54% of the thermal of Italy by 2020 (Ministero dello Sviluppo Economico, 2010) according with the European Union target of a 20% of energy produced by renewable resources by 2020

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<sup>1</sup> This work was submitted for publication on January 28<sup>th</sup> to Apply Energy with the title “Life cycle environmental impact of firewood production - A case study in Italy”

(European Parliament and Council, 2009c). Among the different types of woody materials used for domestic heating in Italy, 92% is constituted by firewood, 4.5% by pellet and 3.5% others (APAT and ARPA, 2008). Although the increasing demand of firewood represents a potential field of economic growth for the wood sector in Italy, in the last decades a dramatic increase of importation of firewood has been observed. In 2012 Italy was acknowledged as the first importer of firewood of the world (Faostat, 2013) a large part of which originating from the Balkans' area. The massive importation of firewood from this area is mainly due to the overall lower cost of labor and of raw materials encountered in these Countries, according to the Kyoto Protocol classified as countries with "economy in transition" indicating the specific socio-economic conditions characterizing the transition phase from previous totalitarian regimes (United Nations, 1997).

Although the use of firewood imported from abroad can be economically convenient, it may have negative consequences on the environment. As far as the global warming is concerned, biomass is considered to be carbon neutral (Cherubini et al., 2009; Helin et al., 2013; Lippke et al., 2011b; McKechnie et al., 2011; McManus, 2010; Routa et al., 2012a, 2012b; Whittaker et al., 2011), since it is considered that the carbon dioxide released in the combustion phase equals the carbon dioxide absorbed during the growth of a same amount of biomass in forest. However this assumption does not consider the emissions of fossil origin generated throughout the life cycle of the product. In this regard, the distance traveled from the site of acquisition of the raw material to the utilization site may play an important role in the overall carbon footprint (Berg, 1997; Heinemann, 2012; Karjalainen and Asikainen, 1996; Michelsen et al., 2008; Solli et al., 2009). It is known that transportation is an important source of carbon dioxide emissions, which have potential impact on climate change (Cespi et al., 2014). However it is not known at what distance this impact becomes critical for the firewood supply chain.

Furthermore, although the impact on global warming is considered to be crucial, some studies have shown that combustion can have a high impact on photochemical smog and human toxicity (Cespi et al., 2014; Solli et al., 2009) but it is not known how a long supply chain would influence these impact categories.

To evaluate the environmental impacts produced by the firewood supply chain the Life Cycle Assessment (LCA) is the internationally recognized tool. LCA, as defined by the ISO 14040 and ISO 14044 standards, is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO, 2006a, 2006b).

Through the LCA it is possible to quantify the environmental impacts in all the phases of the supply chain, from the acquisition of the raw materials from the environment, until the production, distribution and use of the final product. The LCA allows to evaluate the environmental impacts for different impact categories for the compartments: air, water and soil. As far as the air compartment is concerned, the LCA includes some global scale impact categories such as the Global Warming



Potential (GWP) and the Ozone Depletion Potential (ODP) and some local/regional scale impact categories such as the Photochemical Ozone Creation Potential (POCP) and the Human Toxicity Potential (HTP). The GWP or “greenhouse effect” produces an increase of temperature in the lower atmosphere that can lead to climate and environmental changes. The ODP regards the decomposition of the stratospheric ozone layer that causes an increase in the incoming UV-radiation that leads to impacts on humans, natural organisms and ecosystems. No matter where the contributing substances are emitted they contribute to the same phenomenon and GWP and ODP impact categories are therefore considered to be global.

At local scale, the LCA takes into account the photochemical ozone creation and the potential effects of emissions on human health throughout the POCP and the HTP categories. Particularly, all the considered impact categories have an effect on human health but the HTP takes into account also the heavy metals and particles (dust).

Although the emission of pollutants might be critical in the firewood combustion phase, several studies have demonstrated the overall benefit for the environment associated with the use of wood instead of traditional fossil fuels such as coal and natural gas (Cherubini et al., 2009; Lippke et al., 2011b; Sathre and Gustavsson, 2012; Sathre and O’Connor, 2010).

As a renewable material, the harvested wood in forest can be replaced in a relatively short time through the carbon absorption in forest. By saving a part of the biomass increment, a sustainable forest management can aim at offsetting the emissions of the entire firewood supply chain. This specific problem has not been previously addressed and the modality of offsetting and quantifying the benefit of it are still not known.

In this framework the objectives of this study are:

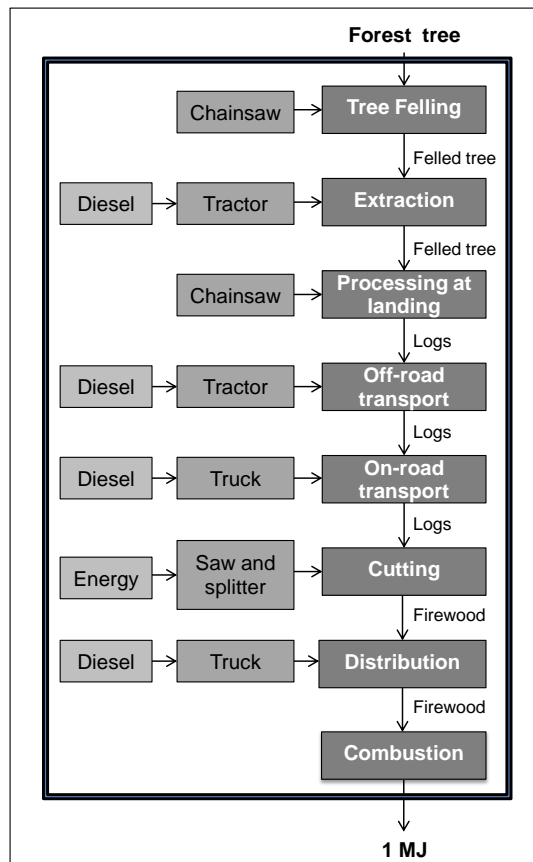
- Evaluate the environmental impacts of short and long firewood supply chain for the four impact categories: GWP, ODP, POCP and HTP;
- Perform a sensitivity analysis to set the critical distance of transportation;
- Assess the carbon offsetting in forest.

### **4.3 Materials and methods**

The product system object of this study is the firewood supply and processing chain based on the forest management of high forest stand of beech (*Fagus sylvatica* L.) which is a common broadleaves tree species in Italy (Nocentini, 2009).

The functional unit is represented by 1 MJ of thermal energy produced from overbark beech wood. The value chain for the production of 1 MJ of thermal energy from wood can be divided into the following main phases: forest management, felling trees, full tree extraction, processing tree at landing, off-road transport, road transport, processing (sawing and splitting), distribution and

combustion. Figure 1.1 shows the firewood supply chain process flow diagram. The system boundary includes all the processes needed to produce 1 MJ of energy from firewood for domestic heating.



**Figure 4.1** Process flow diagram of the investigated firewood supply-chain.

A gate-to-grave approach has been considered in the study since the impacts from the acquisition of the raw material until the end of life have been taken into account.

To evaluate the environmental impacts related to long distance imported logs to produce firewood, two scenarios have been taken into account: (i) the firewood supply chain based on the wood harvested from local forests (short supply chain), (ii) the firewood supply chain based on the processing of logs imported from neighbouring countries as i.e. the Balkans' area (long supply chain).

In the first scenario the exploited forest is located in North-Eastern Italy in the area of Cansiglio forest (46° 4'46.00"N; 12°24'54.00"E). As an alternative the second scenario analyses the firewood supply chain based on the importation of logs from Croatia.

In both scenarios the beech wood density at 50% of moisture content is assumed to be 1117 kg/m<sup>3</sup> until the saw and split process. After air drying the moisture content decreases to 13% and the density changes to 680 kg/m<sup>3</sup> (distribution and combustion phases).

The trees are motor manual felled by a 3.6 kW chainsaw (tree felling) and then hauled as full tree for a short distance (150 m) by a 4WD 67 kW tractor equipped with a winch (extraction). The wood harvesting produces 30% of residues which are left to decompose in forest.

Forest operations are then performed by means of 3.6 kW chainsaw to transform full tree in logs (landing) which are transported off-road by a 4WD 81 kW tractor and trailer with a 11 t payload for a distance of 800 m and then on a truck for the on-road transport. The on-road transport is referred to the transportation along public road to the terminal where logs are cut and splitted. It has been assumed for the on-road transport distance an average value of 25 km and 500 km respectively for the first and the second scenario. Logs are then cut by means of a saw and splitter to produce a wood product suitable to become firewood (saw and splitter process). The saw and splitter machine has been assumed to work at 85% of efficiency. The firewood is then distributed to the final customers by a truck for an average distance of 25k m, assumed constant for both the scenarios.

Through the combustion the firewood is then converted to energy for domestic heating (6 kW). The combustion phase corresponds to the end of life of firewood. According to the lower calorific value of beech firewood (15.5 MJ/kg for a moisture content of 13%) to produce 1 MJ of heat a total amount of 64.5 g needs to be burned.

The data used for this study are both primary and secondary data: primary data were collected for the productivity and the consumptions of the chainsaw in the processes of tree felling and the processing of full tree at landing and transport operations (Cavalli et al., 2011) and for the consumption of energy for the saw and splitter (Cavalli et al., 2014). Primary data were collected on the production site where the study has been conducted and for the physical properties of wood (e.g. moisture content, density, calorific value). Data from the Management Plan were used for the forest management (Regione del Veneto, 2002).

Secondary data have been utilized for the emission factors provided by Ecoinvent database (Frischknecht et al., 2005), internationally recognized by the scientific community to be one of the most complete database to perform LCA studies.

GaBi 6 software has been used to perform the life cycle analysis, to generate the emissions factors and to analyze the relative contribution of the various firewood chain processes to emissions. GaBi 6 is a software package developed by PE International designed for analyzing the environmental impact of products and services over their whole life cycle. The environmental impacts of firewood chain processes have been calculated utilizing the CML 2001 – Apr. 2013 method incorporated within GaBi and developed by the Institute of Environmental Sciences (CML) of Leiden University. As described above, four impact categories associated with air pollution have been selected: two at global scale, Global Warming Potential (GWP) and Ozone Depletion Potential (ODP), and two at local/regional scale, Photochemical Ozone Creation Potential (POCP) and Human Toxicity Potential (HTP).

After the characterization phase of LCA, the impact on each impact categories is expressed in terms of its reference gas. For example, the GWP is expressed in terms of carbon dioxide equivalents (CO<sub>2</sub>-eq). This means that the effect of the greenhouse gas emissions on global warming is referred to the CO<sub>2</sub> by multiplying the concentrations of each greenhouse gas by its Global Warming Potential (GWP). The time frame for the assessment of the global warming impact is 100 years, as recommended by the PAS 2050 (BSI, 2011). As for the GWP, different substances contribute to ozone depletion, photochemical ozone creation and human toxicity: the ODP is expressed in terms of trichlorofluoromethane equivalents (R11eq), the POCP in terms of ethylene equivalents (etheneeq) and the HTP in dichlorobenzene equivalents (DCBeq).

To assess the carbon offsetting, the amount of CO<sub>2</sub> absorbed from the atmosphere can be evaluated by multiplying the amount of carbon in the woody biomass by the molecular weight of CO<sub>2</sub> and divided the molecular weight of carbon as followed (IPCC, 2006):

$$CO_2 = C \frac{MW_{CO_2}}{MW_c}$$

C = total carbon in biomass

MWCO<sub>2</sub> = Molecular weight of CO<sub>2</sub> (44 kg/kmol)

MWC = Molecular weight of carbon (12 kg/kmol)

The total carbon in biomass (C) has been assumed to be the 50% of the total biomass. The data have been extracted from the Forest Management Plan of Cansiglio area.

In the case of Cansiglio, a total area of 4342 ha has been considered, 3539 ha of which of forest. The main function of the forest is wood production (76%), and in the lesser extent, tourism (13%), protection (1.5%) and environmental conservation (9.5%). The predominant species is beech (*Fagus sylvatica* L.), occasionally mixed with spruce and silver fir. The average age of trees has been assumed to be of 100 years and the rotation period is of 70 years.

To estimate the carbon offsetting a representative area where wood is harvested for the production of firewood has been selected. This fraction of area corresponds to the compartments with productive function and with the presence of beech, and encompasses a surface of 2918 ha, 2873 ha of which of forest land. The average volume of biomass in forest is 308 m<sup>3</sup> ha<sup>-1</sup> and the percent average increment is 1.99% (6.11 m<sup>3</sup> yr<sup>-1</sup> ha<sup>-1</sup>). The forest management is natural regeneration with an average harvesting rate of 3.88 m<sup>3</sup> yr<sup>-1</sup> ha<sup>-1</sup> (harvesting rate to increment ratio is equal to 63.5%).

It is assumed that the biogenic CO<sub>2</sub> emitted at the end of life (through combustion) and released during decomposition of residues left in forest is offset by the amount of CO<sub>2</sub> sequestered from the atmosphere for biomass growth.

## 4.4 Results

### 1. Environmental impacts of the short and long supply chain.

The results of the LCA of firewood obtained from logs harvested in local forests (short supply chain) and imported (long supply chain) are summarized respectively in Table 4.1 and Table 4.2

**Table 4.1** Relative contributions of the short supply chain processes to global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and human toxicity potential (HTP) for the production of 1MJ of energy. Note: the biogenic CO<sub>2</sub> has not taken into account in the GWP

Short supply chain				
	GWP [gCO <sub>2eq</sub> ]	ODP [mgR11 <sub>eq</sub> ]	POCP [mgEthene <sub>eq</sub> ]	http [gDCB <sub>eq</sub> ]
<b>Total</b>	<b>4.314</b>	<b>0.218</b>	<b>80.485</b>	<b>9.805</b>
<b>Tree Felling</b>	2.03%	7.67%	4.71%	0.25%
<b>Extraction</b>	0.11%	0.27%	0.01%	0.06%
<b>Processing at landing</b>	2.03%	7.67%	4.71%	0.25%
<b>Off-road transport</b>	0.61%	1.42%	0.03%	0.34%
<b>On-road transport</b>	6.57%	21.42%	0.23%	0.46%
<b>Sawing and splitting</b>	20.32%	35.51%	0.39%	1.99%
<b>Distribution</b>	8.39%	26.05%	0.25%	0.48%
<b>Combustion</b>	59.95%	0.00%	89.68%	96.17%
<b>Total</b>	<b>100.00%</b>	<b>100.00%</b>	<b>100.00%</b>	<b>100.00%</b>

**Table 4.2** Relative contributions of the long supply chain processes to global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and human toxicity potential (HTP) for the production of 1MJ of energy. Note: the biogenic CO<sub>2</sub> has not taken into account in the GWP

Long supply chain				
	GWP [gCO <sub>2eq</sub> ]	ODP [mgR11 <sub>eq</sub> ]	POCP [mgEthene <sub>eq</sub> ]	http [gDCB <sub>eq</sub> ]
<b>Total</b>	<b>9.698</b>	<b>1.104</b>	<b>84.007</b>	<b>10.662</b>
<b>Tree Felling</b>	0.90%	1.51%	4.51%	0.23%
<b>Extraction</b>	0.05%	0.05%	0.01%	0.06%
<b>Processing at landing</b>	0.90%	1.51%	4.51%	0.23%
<b>Off-road transport</b>	0.27%	0.28%	0.03%	0.31%
<b>On-road transport</b>	58.44%	84.50%	4.41%	8.46%
<b>Sawing and splitting</b>	9.04%	7.01%	0.37%	1.83%
<b>Distribution</b>	3.73%	5.14%	0.24%	0.44%
<b>Combustion</b>	26.66%	0.00%	85.92%	88.44%
<b>Total</b>	<b>100.00%</b>	<b>100.00%</b>	<b>100.00%</b>	<b>100.00%</b>

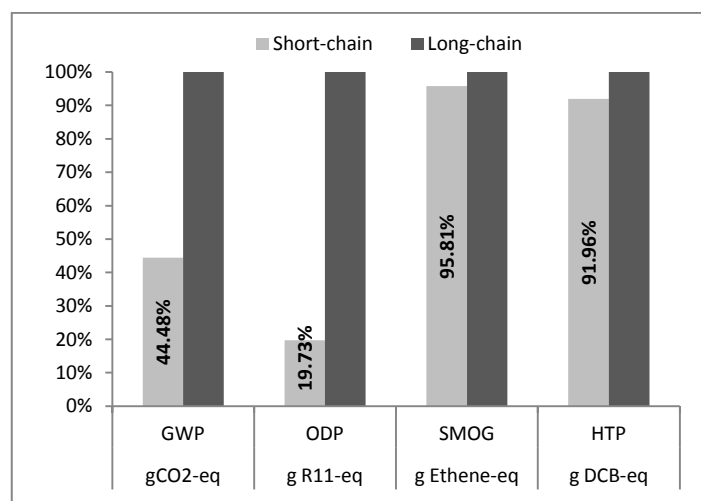
Considering the short supply chain, in all the impact categories, except for ODP, the phase of the life cycle with the highest environmental impact is the combustion. Moreover, for POCP and HTP the combustion represents almost the totality of the impacts (89.68% and 96.17% respectively), and

the impact of the on-road, off-road transport and distribution are negligible.

In the case of the long supply chain, the impact of the on-road transport is higher than the other processes in the global phenomena (GWP and ODP) and lower in the local phenomena (POCP and HTP). In fact, moving from the short supply chain to the long supply chain, the contribute of the on-road transport on the overall impact for the GWP changes from 6.57% to 58.44% and for the ODP from 21.42% to 84.50%.

For POCP and HTP the impact of on-road transport is marginal compared to the combustion. Moving from the short supply chain to the long supply chain, POCP changes from 0.12% to 4.41% and HTP changes from 0.46% to 8.46%.

Comparing the overall impact of the short supply chain to the long supply chain, as shown in Figure 4.2, excluding the biogenic emissions, the GWP of the long supply chain is more than double than the GWP of the short supply chain and the ODP of the long supply chain is five times the ODP of the short supply chain.



**Figure 4.2** Short and long firewood supply chains comparison in term of environmental impacts (GWP=Global Warming Potential; ODP=Ozone Depletion Potential; POCP=Photochemical Ozone Creation Potential; HTP=Human Toxicity Potential. Note: the biogenic CO<sub>2</sub> has not taken into account in the GWP)

By contrast, the SMOG and the HTP values are comparable in the two cases.

To understand why the long supply chain has a bigger influence on global phenomena than local phenomena the list of chemicals emitted has to be investigated. **Errore. L'origine riferimento non stata trovata.**3 reports the values of the total emissions generated in the two scenarios, for the four impact categories. The two columns “Characterization” and “Inventory” represent respectively the results after and before characterization (the phase of the LCA which attributes the impact of different chemicals in terms of a reference gas). The chemicals are sorted by their values after characterization, in decreasing order.

**Table 4.3** Relative contributions of chemicals in the short and in the long supply chain for the production of 1MJ of energy. The values are referred to the emissions after characterization (“Characterization” column) and before characterization (“Inventory” column) for global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and human toxicity potential (HTP)

	Short supply chain		Long supply chain	
	Characterization	Inventory	Characterization	Inventory
<b>GWP</b>	gCO <sub>2e</sub>	g	gCO <sub>2e</sub>	g
<b>Emissions to air (total)</b>	<b>101.627</b>	<b>101.690</b>	<b>107.027</b>	<b>106.885</b>
Carbon dioxide (biotic)	97.313	97.313	97.328	97.328
Carbon dioxide	1.617	1.617	6.745	6.745
Nitrous oxide (laughing gas)	2.120	0.007	2.169	0.007
Methane (biotic)	0.501	0.020	0.502	0.020
Methane	0.067	0.003	0.250	0.010
Group NMVOC to air	0.004	1.96E-06	0.027	1.21E-05
Sulphur hexafluoride	0.004	1.74E-07	0.005	2.23E-07
<b>ODP</b>	µgR11 <sub>eq</sub>	µg	µgR11 <sub>eq</sub>	µg
<b>Halogenated organic emissions to air*</b>	<b>0.218</b>	<b>0.058</b>	<b>1.104</b>	<b>0.159</b>
*Halon (1301), Halon (1211), R 22 (chlorodifluoromethane), R 114 (dichlorotetrafluoroethane), Carbon tetrachloride (tetrachloromethane), R 12 (dichlorodifluoromethane), R 113 (trichlorotrifluoroethane), Chloromethane (methyl chloride), R 11 (trichlorofluoromethane), 1,1,1-Trichloroethane				
<b>POPC</b>	mgEthene <sub>eq</sub>	mg	mgEthene <sub>eq</sub>	mg
<b>Emissions to air (total)</b>	<b>80.485</b>	<b>2596.987</b>	<b>84.007</b>	<b>2644.132</b>
Carbon monoxide (biotic)	62.100	2300.005	62.100	2300.012
Group NMVOC to air*	11.348	30.836	13.792	37.571
Nitrogen oxides	5.419	193.520	5.965	213.021
Carbon monoxide	1.175	43.520	1.384	51.258
Sulphur dioxide	0.306	6.380	0.586	12.202
Methane (biotic)	0.120	20.043	0.120	20.065
Methane	0.016	2.682	0.060	10.002
*1,1,1-Trichloroethane, Chloromethane (methyl chloride), Dichloromethane (methylene chloride), Tetrachloroethane (perchloroethylene), Trichloromethane (chloroform), Vinyl chloride (VCM; chloroethene), 1-Butanol, 1-Pentene, 2-Methyl-2-butene, Acetaldehyde (Ethanal), Acetic acid, Acetone (dimethylketone), Alkane (unspecified), Benzaldehyde, Benzene, Butadiene, Butane, Butanone (methyl ethyl ketone), Cumene (isopropylbenzene), Ethane, Ethanol, Ethene (ethylene), Ethine (acetylene), Ethyl benzene, Ethylene acetate (ethyl acetate), Formaldehyde (methanal), Formic acid (methane acid), Heptane (isomers), Hexane (isomers), iso-Butanol, Isoprene, Isopropanol, Methanol, Methyl acetate, Methyl formate, Methyl tert-butylether, NMVOC (unspecified), Pentane (n-pentane), Propane, Propene (propylene), Propionaldehyde, Propionic acid (propane acid), Styrene, Toluene (methyl benzene), Xylene (dimethyl benzene), Xylene (meta-Xylene; 1,3-Dimethylbenzene)				
<b>HTP</b>	mgDCB <sub>eq</sub>	mg	mgDCB <sub>eq</sub>	mg
<b>Heavy metals to air*</b>	<b>1162.885</b>	<b>0.374</b>	<b>1548.155</b>	<b>0.401</b>
*Arsenic (+V), Nickel (+II), Chromium (+VI), Cadmium (+II), Copper (+II), Zinc (+II), Vanadium (+III), Lead (+II), Chromium (unspecified), Selenium, Mercury (+II), Cobalt, Antimony, Molybdenum, Thallium, Tin (+IV), Hydrogen arsenic (arsine)				
<b>Inorganic emissions to air*</b>	<b>252.630</b>	<b>201.742</b>	<b>300.704</b>	<b>227.207</b>
*Nitrogen oxides, Hydrogen fluoride, Sulphur dioxide, Ammonia, Beryllium, Barium, Carbon disulphide, Hydrogen chloride, Hydrogen sulphide				
<b>Organic emissions to air (group VOC)</b>	<b>8267.884</b>	<b>29.690</b>	<b>8688.314</b>	<b>35.915</b>
Polycyclic aromatic hydrocarbons (PAH)	6466.755	0.011	6851.513	0.012
Other organic emissions to air*	1739.909	29.678	1766.846	35.903
Halogenated organic emissions to air**	61.219	9.28E-05	69.955	1.66E-04
*Benzene, NMVOC (unspecified), Formaldehyde (methanal), Toluene (methyl benzene), Propylene oxide, Ethyl benzene, Ethylene oxide, Xylene (meta-Xylene; 1,3-Dimethylbenzene), Ethene (ethylene), Xylene (dimethyl benzene), Butadiene, Acrolein, Phenol (hydroxy benzene), Styrene				
**Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD), Hexachlorobenzene (Perchlorobenzene), Vinyl chloride (VCM; chloroethene), Dichloroethane (ethylene dichloride), Carbon tetrachloride (tetrachloromethane), Pentachlorophenol (PCP), Trichloromethane (chloroform), Dichlorobenzene (o-DCB; 1,2-dichlorobenzene), 2,4-Dichlorophenol, Pentachlorobenzene, Dichloromethane (methylene chloride), 1,1,1-Trichloroethane, Tetrachloroethane (perchloroethylene), Methyl bromide				
<b>Particles</b>	<b>121.841</b>	<b>148.627</b>	<b>124.855</b>	<b>152.372</b>
Dust (PM <sub>2.5</sub> )	96.167	117.276	97.003	118.296
Dust (> PM <sub>10</sub> )	25.519	31.120	26.859	32.755
Dust (PM <sub>2.5</sub> - PM <sub>10</sub> )	0.154	0.188	0.988	1.204
Silicon dust	0.001	0.001	0.005	0.007

## GWP

As far as the GWP is concerned, the majority of the emissions are constituted of biogenic carbon dioxide produced by the combustion of biomass to produce energy. The method of evaluation of the biogenic emissions is still object of discussion at international level because they are often assumed equal to the carbon sequestered in forest and neglected. Based on international standards

and guidelines, the biogenic carbon dioxide is not accounted in LCA studies (carbon neutrality assumption) or is reported separately (EPA, 2011; European Commission, 2010; ISO, 2006a, 2006b).

Unlike the CO<sub>2</sub> which can be offset by the activity of absorption of trees, methane, also of biogenic origin, cannot be neutralized and it necessarily has to be included in the accounting.

Including the biogenic CO<sub>2</sub> emissions, the impact on global warming for the production of 1 MJ of energy for domestic heating from firewood in the whole life cycle for the short supply chain is 102 gCO<sub>2</sub>eq, for the long supply chain is 107 gCO<sub>2</sub>eq. Excluding the biogenic CO<sub>2</sub> emissions, the GWP is 4.314 gCO<sub>2</sub>eq and 9.698 gCO<sub>2</sub>eq respectively for the short and the long supply chain, the latter being more than twice the former.

The biogenic CO<sub>2</sub> and methane are products of the combustion phase, while the on-road transport is responsible for the majority of the emissions of fossil CO<sub>2</sub>, organic emissions (fossil methane and non methane volatile organic compounds – NMVOC), halogenated emissions and sulphur hexafluoride.

#### ODP

Regarding the ozone depletion, the phenomenon is not influenced by the combustion since the chemical substances responsible for it are not emitted during this phase of the life cycle. As previously outlined, moving from the short to the long supply chain the ODP increases considerably. The ODP of the long supply chain (1.104 µgR11eq) in fact is five times the ODP of the short supply chain (0.218 µgR11eq). However it should be noticed that the quantity of chemicals with potential impact on ozone depletion are emitted in a very small quantity in terms of absolute values.

#### POPC

Differently from GWP and ODP which are highly influenced by the phase of on-road transport, the photochemical smog values are comparable in the two scenarios (respectively 84.007 mgEtheneeq and 80.485 mgEtheneeq for the long and the short supply chains). The potential impact on photochemical ozone creation potential is predominantly caused by combustion. This phase in fact produces a considerable amount of carbon monoxide which is associated with the process conditions e.g. the efficiency of combustion and the abundance of oxygen. Carbon monoxide constitutes the 77.16% and 73.92% of the impact on POPC respectively in the short and long supply chains. The rest of the potential impact on POPC is determined by the group NMVOC, nitrogen oxides, fossil carbon monoxide, sulphure dioxide and methane. Among these, the on-road transport is responsible of the majority of emissions of nitrogen oxides and NMVOC while the combustion phase of carbon monoxide, sulphure oxides and halogenated emissions.



## HTP

Similarly to the POPC, the on-road transport has little influence on HTP. In fact for the long and the short supply chains the values are respectively 10.662gDCBeq and 9.805 gDCBeq. The impact on human toxicity regards four main groups of pollutants: heavy metals, inorganic emissions, organic emissions (VOC) and particles. As mentioned above, in the LCA of firewood the impact on human health is dominated by the combustion phase which contributes for 96.17% and 88.44% of the total respectively in the short and long supply chain.

In terms of contributions, the four groups of pollutants are sorted as (in decreasing order): organic emissions, heavy metals, inorganic emissions and particles. Organic emissions produced by combustion include polycyclic aromatic hydrocarbons, halogenated organic emissions, polychlorinated dibenzo-p-dioxins (2,3,7,8-TCDD), benzene and formaldehyde. Among this, the most dangerous one for the human health is constituted by the 2,3,7,8-TCDD. As it can be observed from Table 3, comparing the values of 2,3,7,8-TCDD before and after characterization, a small amount of this chemical (92.771 ng) causes 98.90% of the impact on human health associated with the halogenated organic emissions (60.548 mgDCBeq).

Heavy metals are contained into the woody biomass and are released in the combustion phase. Among the most dangerous for the huma

n health there are: arsenic (+V), nickel (+II), chromium (+VI), cadmium (+II), lead (+II).

The inorganic emissions, already accounted for other impact categories such as GWP and POPC, also have a direct impact on human health. The most critical are represented by nitrogen oxides, hydrogen fluoride, hydrogen chloride and ammonia, the latter typically released during combustion.

Lastly the combustion phase is responsible of the production of particles, especially fine and ultrafine (PM<sub>2.5</sub>).

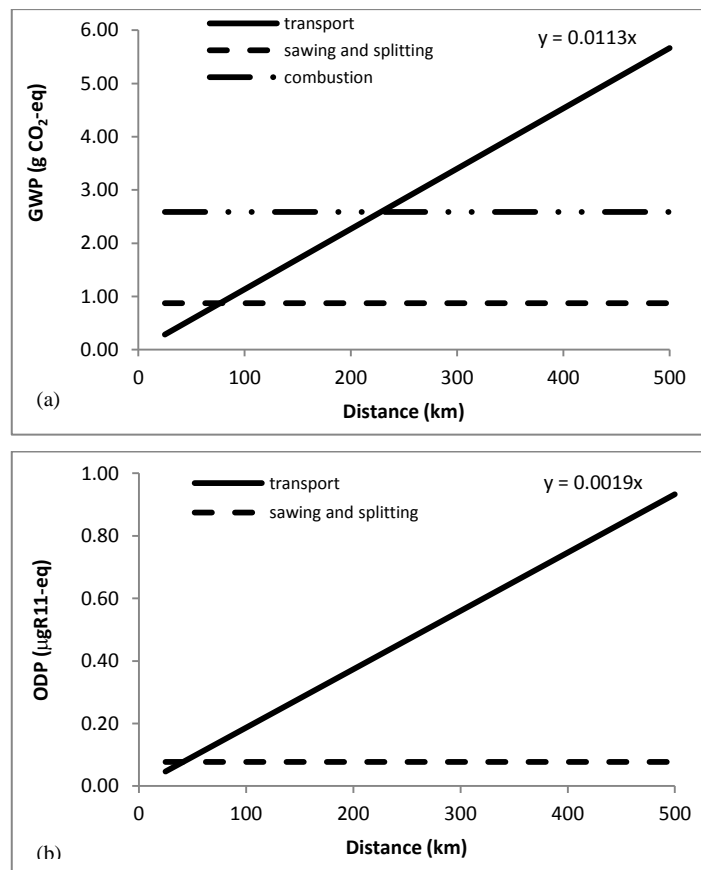
## ***2. Sensitivity analysis for the evaluation of the critical distance of transportation***

The results of the LCA show that the extraction of wood from a forest located in the Balkans' area and the consequent transportation of the raw material to the production site generates different effects on the four impact categories considered. However the results obtained depends on the specific assumptions of the case study. To have a clearer picture of how, in general, the length of the supply chain influences the LCA of firewood, it has been evaluated what is the distance after which the supply chain becomes critical for each impact category, keeping constant the characteristics of the rest of the life cycle.

A sensitivity analysis has been performed to determine the critical distance after which the on-road transport becomes the dominant contributor to GWP, ODP, POCP and HTP. For GWP and ODP the distance has been changed between the range 25-500 km and, through a linear regression, it has

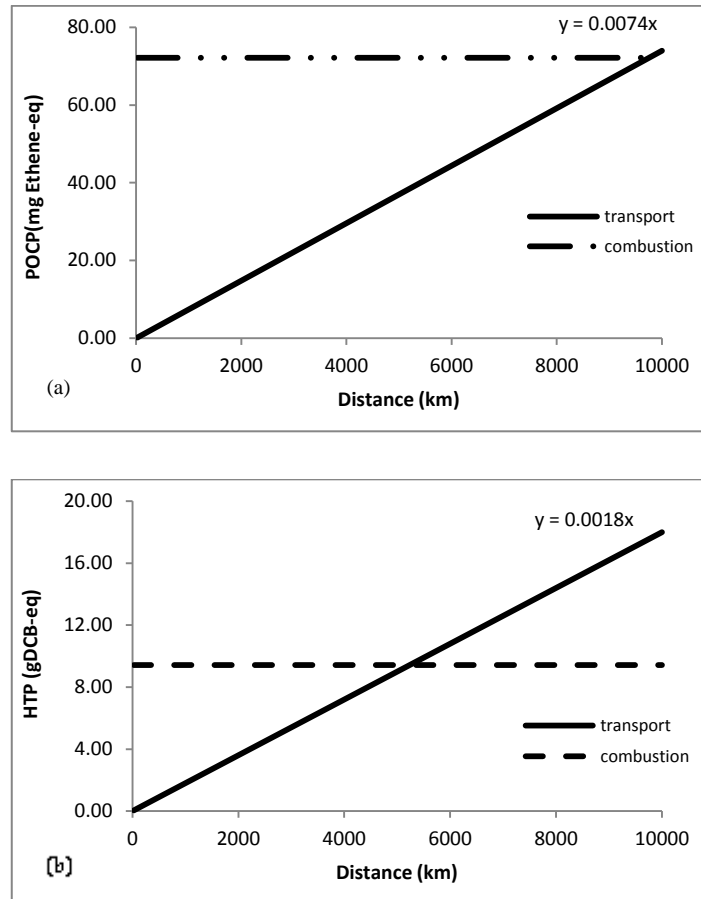
been possible to determine the equation representative of the impact associated with the transportation and the critical values.

As shown in Figure 4.3 a) and b) when the distance equals 229 km and 41 km the on-road transport becomes the critical phase respectively for GWP and ODP with respect to the combustion process. Compared to the firewood sawing and splitting 78 km is also the distance after which the on-road transport becomes critical in terms of GWP.



**Figure 4.3** Sensitivity analysis for (a) g CO<sub>2</sub>-eq and (b) g R11 - eq emissions as a function of the road transport phase distance.

As far as the POCP and HTP are concerned, the same approach has been used to compare the impact of on-road transport to combustion and the distance has been changed between 25 km to 10000 km. As shown in Figure 4.4 a and b, the critical values obtained are respectively 9754 km and 5239 km for POCP and HTP.



**Figure 4.4** Sensitivity analysis for (a) mg Ethene – eq and (b) g DCB – eq emissions as a function of the road transport phase distance.

### 3. Carbon offsetting in forest

If in the GWP the biogenic carbon was considered, surely the combustion would have been the most critical phase but, as mentioned above, how to consider the biogenic carbon is still debated in the LCA. In fact to evaluate the impact on global warming correctly it is necessary to consider the total carbon balance.

Conventionally it is assumed that the biogenic CO<sub>2</sub> emitted at the end of life of the product equals the CO<sub>2</sub> previously absorbed from the atmosphere. However it is possible to evaluate the total amount of biomass which is needed to be saved in forest to offset the fossil emissions of the overall supply chain.

As far as the fossil CO<sub>2</sub> emissions are concerned, based on the lower calorific value (15.5 MJ kg<sup>-1</sup>, moisture content 13%) and the density (680 kg m<sup>-3</sup>), one cubic meter of firewood produces 10540 MJ of energy which, multiplying it by the emissions of the LCA in the two scenarios, produces a total amount of fossil emissions of 45.47 and 102.22 kgCO<sub>2</sub>eq respectively.

For the selected area, considering that 30% of the harvested wood is constituted of residues which

are left in forest to decompose, for a harvesting rate of 3.88 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> a total amount of 2.72 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> of firewood is produced, which in the two scenarios generates respectively 123.49 and 277.63 kgCO<sub>2</sub>eq of fossil emissions.

Applying the inverse formula, it has been found that the biomass increment necessary to offset the life cycle of firewood is respectively 0.096 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> and 0.216 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> which corresponds to 4.32% and 9.70% of the biomass increment which remains in forest after harvesting.

It is possible to affirm that, with the type of forest management performed in the Cansiglio area, the emissions of the life cycle of firewood are totally offset in both cases by less than 10% of the net increment of biomass. Similarly it has been calculated what is the maximum harvesting rate which can be adopted in the area in order to have carbon neutral firewood. The result shows that, referring to the local wood scenario, it is possible to harvest 97% of the increment and the remaining 3% would offset the fossil emissions produced in the whole life cycle of firewood. Furthermore, by applying the regression equation for GWP calculated in the sensitivity analysis, the maximum distance that could be traveled in order to have carbon neutral firewood with the current value of harvesting rate in the Cansiglio area is around 8500 km.

With the current harvesting rate, in fact, since the forest growth biomass is higher than the harvested biomass, the carbon absorption of the standing tree in forest completely offset the carbon emissions of the whole life cycle of the firewood produced by the wood harvested in the whole area up to a transportation distance of 8500km. Within this distance with the current forest management, the firewood can be considered carbon neutral.

#### **4.5 Discussion**

Comparing the results of this study with the literature, there is congruency between the values of GWP obtained and the ones presented by the European Commission Joint Research Centre (Agostini et al., 2013). which, including the biogenic emissions, refers a total value of 102gCO<sub>2</sub>eq/MJ energy from biomass.

The results obtained for the short supply chain can be generalized to firewood locally produced in Italy. In fact a large majority of it (75%) is produced in the Northern Italy (Regione Liguria, 2005). Moreover in the Alpine area typically a similar technology is used (low level of forest mechanization, short distance between the forest and the manufacturing site).

This statement is supported by the study performed by (Valente et al., 2011) which analyzed the energy wood supply chain in Valle di Fiemme, Italy. The study outlines similar findings for the allocation of the environmental impacts throughout the supply chain. A marginal contribution of the phases of felling, extraction and landing operation in terms of impact on global warming was

found, reflecting the low level of mechanization of forest operations similar to the one herein described.

The results of the long supply chain scenario can be applied to any other context where the level of mechanization is comparable. The technology used for forest operations has been purposely assumed equal in both scenarios to outline the effect of transportation keeping constant the other variables.

However the sensitivity analysis performed to determine the distance after which the transportation becomes critical within the supply chain has general validity, as long as the combustion is the competitive phase of transportation. It was found that the critical distance after which the transportation becomes the most important source of emissions affecting global warming is around 9 times the distance of the short supply chain. The same results were found for a Norwegian case study by (Solli et al., 2009), who found that the transportation became the critical phase in terms of global warming if the distance of the short supply chain was multiplied by 4 to 5, assuming a distance equal to twice (50 km) the distance assumed in this study (25 km) for the short supply chain.

In general, combustion being a critical phase in terms of pollutants emissions is also coherent with some studies in the literature (Cespi et al., 2014; Solli et al., 2009). It has been recognized that the main variables affecting the emissions are, on one hand, the combustion and pollutant removal efficiency, and, on the other hand, the fuel type and composition (Cespi et al., 2014). The mode of burning is related to how often new wood is fed into the stove and how much air is available for combustion (Solli et al., 2009). The efficiency of the stove is then related to the technology involved.

To better understand the results, it should be noticed that, based on the APAT - ARPA data, the national annual consumption of firewood is around 20 Mt, corresponding to an annual average consumption per inhabitant of 4.3 t of firewood. In mountain areas the annual average consumption per inhabitant is 5.2 t of firewood (APAT and ARPA, 2008). Considering the lower calorific value of beech firewood (15.5 MJ kg<sup>-1</sup> at a moisture content of 13%) respectively 67 GJ and 81 GJ are needed per year per inhabitant in average and in mountain areas.

As far as the impact offset is concerned, this study has shown that, in both cases, as long as 10% of the biomass increment is preserved in forest, the whole supply chain of the firewood can be considered carbon neutral since the absorption of CO<sub>2</sub> offsets the fossil emissions throughout the life cycle. However, it should be noticed that the impact on global warming is conventionally expressed in terms of CO<sub>2</sub>eq because the carbon dioxide is the most widespread greenhouse gas in the atmosphere, but, as shown in Table 3, the emitted greenhouse gases include methane, nitrous oxide, sulphur hexafluoride and volatile organic compounds. None of them, despite being expressed in terms of carbon dioxide to assess their impact on global warming, is able to be offset

through the carbon absorption in forest. These greenhouse gases will stay in the atmosphere for a time equal to their permanence time contributing to global warming.

Moreover, all the chemicals emitted throughout the life cycle that have an impact on ozone depletion, photochemical ozone creation and human toxicity are not possible to offset.

However, although these pollutants are emitted in the atmosphere, certainly they are produced in smaller quantities if compared with the combustion of fossil fuels. As shown by the study of Dwivedi et al., 2012; Valente et al. (2011) the benefit of replacing fossil fuel (fuel oil and natural gas) with wood is clear.

## **4.6 Conclusions**

In this study the life cycle assessment of firewood has been performed, to evaluate the contribute of the long supply chain on the overall impact. Two scenarios have been analyzed, the former representing a local supply chain located in the area of Cansiglio in Italy and the latter adding to the same supply chain the importation of the raw material from the Balkans' area.

The aims of the study were to evaluate the environmental impact of firewood comparing the short and the long supply chain, to perform a sensitivity analysis to set the critical distance of transportation and to assess the carbon offset in forest.

The study has outlined that for the short supply chain the critical phase of the life cycle in terms of GWP, POPC and HTP is combustion. On the contrary, tree felling, extraction, landing and on-road transport have marginal contribution to the overall impact. Moving to the long supply chain, excluding the emissions of biogenic CO<sub>2</sub>, the contribution to GWP of the on-road transport becomes more than double than in the short supply chain and five times higher to ODP turning the on-road transport into the most critical phase. Conversely the impact on POPC and HTP does not undergo large variations.

The on-road transport is responsible of a large amount of fossil CO<sub>2</sub> and volatile organic compounds emitted into the atmosphere that contribute to GWP and of the emissions of some chemicals with potential impact on ODP.

To cause potential impact on POPC, contrary to what expected, is the combustion phase because it emits a large quantity of biogenic carbon monoxide. As far as HTP is concerned, the combustion phase produces organic emissions (polycyclic aromatic hydrocarbons, halogenated emissions, dioxins and formaldehyde), heavy metals, inorganic emissions (nitrogen oxides, hydrogen fluoride and chloride, ammonia) and fine and ultrafine particles.

The study has shown that there are different critical values of transportation distance for impact categories.

Although most of the chemicals emitted in the life cycle of firewood cannot be offset, a sustainable

forest management in the Cansiglio area can completely offset the fossil CO<sub>2</sub> emissions of the short and the long supply chain by saving less than 10% of the net increment. With the current forest management adopted in the area, the emissions of the whole supply chain are offset by the carbon dioxide absorbed by the standing biomass up to a transportation distance of 8500 km, thus producing a carbon neutral firewood.





# Chapter 5

## Life Cycle Assessment of wood chips for bio-energy

The work presented in this chapter is the result of the collaboration with Prof. Ganguly Indroneil<sup>1</sup>, Bowers Tait<sup>1</sup> and Prof. Eastin Ivan<sup>1</sup> whom the author gratefully acknowledge.

The research was performed at the School of Environmental and Forest Sciences, University of Washington, Seattle, WA, United States from May 13<sup>th</sup>, 2013 to May 12<sup>th</sup>, 2014, as part of the NARA project.

### 5.1 The NARA Project

The aim of the Northwest Advanced Renewables Alliance (NARA) Project is to develop regional bio-fuel solutions that are economically viable, socially acceptable and meet the environmental standards of the Pacific Northwest. NARA is a team of scientists from public universities, government laboratories and private industries from the Northwest of United States joining together to focus on sustainability.

The NARA project is a \$40 million project supported by the Agriculture and Food Research Initiative Competitive Grant no. 2011-68005-30416 from the USDA National Institute of Food and Agriculture.

Washington State University is the performing organization assigned to administer the grant.






The NARA team is composed by ([www.nararenewables.org](http://www.nararenewables.org)):

	Washington State University		Western Washington University
	University of Washington		Salish Kootenai College
	Montana State University		Catchlight Energy
	Oregon State University		Facing the Future
	The Pennsylvania State University		Gevo
	University of Idaho		Weyerhaeuser



**Figure 5.1** Organizations participating in the NARA Project.

The Alliance is organized in five specific areas of focus:

-  Education: engage citizens, meet future workforce needs, enhance science literacy in biofuels, and help people understand how they're going to fit into the new energy economy
-  Sustainability Measurement: evaluate and assess environmental, social and economic viability of the overall wood to biofuels supply chain, guiding the project as it goes forward
-  Feedstock: take a multi-pronged approach for the development and sustainable production of feedstocks made from wood materials, including forest and mill residues, municipal solid waste, and speciality energy crops
-  Conversion: provide a biomass-derived replacement for aviation fuel and other petroleum-derived chemicals in a way that is economically and technologically feasible
-  Outreach: serve as a conduit between researchers and community stakeholders, helping to transfer the science and technology of biofuels and important co-products to communities in the Northwest.

The University of Washington role is to perform the Life Cycle Assessment of the overall supply chain. The Life Cycle Assessment encompasses the entire production process of the bio-fuels starting from woody biomass coming from residuals of forest operations.

The project looks at using forest residuals (woody biomass) derived from timber harvest and forest thinning operations. The assessment includes a variety of biofuel feedstocks and harvesting options, the bio-jet fuel conversion process and the impact of the integration of jet fuel manufacturing into existing forest product industries and infrastructure.

The development of advanced biofuels from woody biomass is considered an avenue to attain domestic independence from foreign oil, revitalizing the rural economies and reducing the environmental impact.

The Life Cycle Assessment (LCA) compares petroleum and bio-based fuels along a variety of environmental attributes, including energy use, greenhouse gas emissions and other environmental measures.

The LCA is crucial in demonstrating whether or not bio-jet fuel produced from forest residuals meets the greenhouse gas reduction target specified in the US Energy Independence Act of 2007

(U.S. Government, 2007). The IEA requires that the overall GHG emissions of cellulosic biofuel produce 60% lower carbon emissions in order to be considered for public procurement (<http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf>).

## 5.2 The CORRIM Database

Data for forest operations and processes have been collected by the Consortium for Research on Renewable Industrial Materials (CORRIM). CORRIM developed extensive databases on wood harvesting and processing that will be expanded through the collaboration in the NARA Project. The scenarios draw on analysis developed for the harvest of timber for structural wood products and paper in the first two phases of research by CORRIM.

The two phases of research of the CORRIM project were designed to:

- 1) Collect environmental and economic data on all life-cycle stages from planting and growing the renewable raw material through the manufacturing of product, and to transport, design and construct buildings as well as activities associated with occupation, use and final demolition (Life Cycle Inventories (LCI));
- 2) Ensure that the data follows consistent definitions and collection procedures;
- 3) Develop analytical procedures that facilitate integration of results across the full life-cycle for all stages of processing to address environmental performance questions (Life Cycle Analysis (LCA)).

Data of woody biomass are present in the CORRIM database for different regions: Inland West, North Central, Northeast, Pacific Northwest and Southeast. The database includes scenarios for recovery of logging residuals in the Inland west including Montana, Idaho, and Eastern Washington and from thinning forest stands in the Southeastern United States.

The analysis grouped productive timberlands according to:

- Site productivity
- Management intensity: ranged from restoration thinning treatments on select acres of National Forest land to higher management intensities involving planting and thinning on high productivity private lands.
- Ownership into three broad forest types.

CORRIM database includes the following scenarios for the recovery of landing residues:

- 1 Grind residue and haul from primary landing
- 2 Grind residue from primary landing and shuttle to secondary landing
- 3 Shuttle loose residue from primary landing for grinding and hauling

Twenty-five scenarios have been developed for different harvesting systems:

- 1 Southeast Small Mechanized
- 2 Southeast Large Mechanized

- 3 Pacific Northwest Steep Slopes – Thinning
- 4 Pacific Northwest Steep Slopes – Clearcut
- 5 Pacific Northwest Gentle Mechanized
- 6 Pacific Northwest Gentle Cut-to-Length
- 7 Inland West Steep Slope – Thinning
- 8 Inland West Steep Slope – Clearcut
- 9 Inland West Gentle Mechanized
- 10 Inland West Gentle - Cut-to-Length
- 11 Northeast Gentle Manual
- 12 Northeast Gentle Mechanized
- 13 Northeast Gentle - Cut-to Length
- 14 Northeast Steep Slope Cable
- 15 North Central Gentle Manual
- 16 North Central Gentle Mechanized
- 17 North Central Gentle - Cut-to-Length
- 18 Small Helicopter
- 19 Medium Helicopter
- 20 Large Helicopter
- 21 Biomass from Landing Slash Direct to Mill
- 22 Biomass from Landing through Intermediate Load Site
- 23 Process Post Harvest Residue at Central Site
- 24 Post Harvest Recovery through Intermediate Load Site
- 25 Biomass from Thinning

Nine scenarios have been considered for different methods of slash disposal and recovery:

- 0 No Slash Disposal Conducted
- 1 Whole Tree Operation with Piling at Landing
- 2 Whole Tree Operation with Piling at Landing and Piling in Woods
- 3 Whole Tree Operation with Piling at Landing and Broadcast Burn
- 4 Bole Only Operation with Piling in Woods
- 5 Bole Only Operation with Broadcast Burn
- 6 Recovery and Processing Landing Biomass and Broadcast Burn Woods
- 7 Recovery and Processing of biomass piled at landing
- 8 Recovery and Processing of biomass left in the woods
- 9 Processing biomass at landing PLUS recovery of biomass in woods

CORRIM database include data for the equipments listed in **Errore. L'origine riferimento non è stata trovata.**1. Data have been connected about potential production rate, machine rate, fuel consumption, actual production, horse power for each of the machine.

**Table 5.1** List of forest equipments included in the CORRIM database.

<b>FELLING AND PROCESSING EQUIPMENT</b>	Medium tracked grapple crawler, thin
<b>FELLING</b>	Large tracked grapple crawler, thin
Hand felling, thin	Small tracked grapple crawler, CC
Medium feller buncher, thin	Medium tracked grapple crawler, CC
Large feller buncher, thin	Large tracked grapple crawler, CC
Hand felling, CC	
Medium feller buncher, CC	<b>FORWARDERS</b>
Large feller buncher, CC	Small forwarder, thin
Small cut to length processor, thin	Medium forwarder, thin
Large cut to length processor, thin	Large forwarder, thin
Small cut to length processor, CC	Small forwarder, CC
Large cut to length processor, CC	Medium forwarder, CC
	Large forwarder, CC
<b>PROCESSING</b>	
Chainsaw delimiting	<b>CABLE AND AERIAL YARDING EQUIPMENT</b>
Slide boom delimeter	<b>SKYLINE</b>
Medium dangle head processor	Small skyline, thin
Large dangle head processor	Medium skyline, thin
Fixed base landing delimeter	Large skyline, thin
Fixed base landing processor	Small skyline, CC
<b>GROUND SKIDDING AND FORWARDING EQUIPMENT</b>	Medium skyline, CC
<b>WHEELED SKIDDERS</b>	Large skyline, CC
Small cable skidder, thin	<b>HELICOPTER</b>
Medium cable skidder, thin	Small helicopter, thin
Large cable skidder, thin	Medium helicopter, thin
Small cable skidder, CC	Large helicopter, thin
Medium cable skidder, CC	Small helicopter, CC
Large cable skidder, CC	Medium helicopter, CC
Small grapple skidder,	Large helicopter, CC
Medium grapple skidder, thin	
Large grapple skidder, thin	<b>LOADING EQUIPMENT</b>
Small grapple skidder, CC	Small loader
Medium grapple skidder, CC	Medium loader
Large grapple skidder, CC	Large loader
<b>TRACKED SKIDDERS (CRAWLERS)</b>	Front loader
Small tracked cable crawler, thin	
Medium tracked cable crawler, thin	<b>HAULING EQUIPMENT</b>
Large tracked cable crawler, thin	Truck, with Western log trailer
Small tracked cable crawler, CC	Truck, with 5 <sup>th</sup> wheel straight trailer
Medium tracked cable crawler, CC	Truck, three axle short log
Large tracked cable crawler, CC	Truck, three axle short log and trailer
Small tracked grapple crawler, thin	
<b>TYPE OF MACHINE</b>	
<b>FELLING EQUIPMENT</b>	
Biomass Bundler	
Medium Biomass Feller Buncher	
Large Biomass Feller Buncher	
<b>SKIDDING AND FORWARDING EQUIPMENT</b>	
Medium Biomass Skidder	
Large Biomass Skidder	
Bundle Forwarder	
<b>PROCESSING EQUIPMENT</b>	
Tub Grinder	
Centralized Horizontal Grinder	
On Site Horizontal Grinder	
Small Whole Tree Chipper	
Medium Whole Tree Chipper	

Large Whole Tree Chipper	
<b>LOADING - PILING EQUIPMENT</b>	
Front End Loader	
Large Loader	
Centralized Yard Conveyor	
<b>HAULING EQUIPMENT</b>	
Chip Van - 140 CY - Loaded from Stockpile	
Chip Van - 140 CY - Direct from Landing Grinder	
Chip Van - 140 CY - From Central Grinder	
Chip Van - 120 CY - Loaded from Stockpile	
Chip Van - 120 CY - Direct From Landing Grinder	
Chip Van - 120 CY - From Central Grinder	
Chip Van - 120 CY - w/Small Chipper	
Chip Van - 120 CY - w/Medium Chipper	
Chip Van - 120 CY - w/Large Chipper	
Dump Truck- Modified - Ground Biomass	
Dump Truck- Modified - Ground Biomass - On Highway	
Dump Truck- Modified - Loose Residue	
Off Highway Dump Truck	
End Dump Trailer	
End Dump Trailer - On Highway	
Roll Off Container and Pup Trailer	
Roll Off Container and Pup Trailer - On Highway	
Roll Off Container - Loose Residue	
Roll Off Container - Ground Biomass	
Roll Off Container - Ground Biomass - On Highway	

### **5.3 Abstract**

In the Pacific Northwest most of the woody biomass produced in forest harvest operations is generally collected, piled, and burned in the forest or simply left on the forest floor to decompose. This chapter assesses the environmental implications of recovering these harvest residues to produce woody bio-energy. A comprehensive Life Cycle Assessment (LCA) has been performed with a “cradle-to-grave” approach, where “cradle” is the natural regeneration of young trees within the forest and “grave” is the biomass combustion to produce energy. A range of biomass transportation scenarios has been explored and the avoided environmental costs associated with piling and burning the woody biomass within the forest have been incorporated into the LCA calculations. The environmental impacts of woody bio-energy have also been compared with the impacts of fossil based energy. The environmental burdens have been assessed in terms of global warming, ozone depletion, photochemical smog and human toxicity potentials.

Results obtained indicate that transportation of loose residue in forest road contributes significantly to the overall carbon footprint of woody feedstock. Forest road conditions, limiting use of trucks with higher load carrying capacity to the primary landing, makes the feedstock logistics more carbon intensive. The avoided environmental impacts derived from recovering residuals rather than burning them in slash piles proved to be substantial. The results show that, under certain scenarios, the combustion of woody biomass shows a 60% or greater reduction in global warming potential from carbon dioxide when compared to traditional fossil fuel.

### **5.4 Introduction**

Typical forest harvest operations in the Pacific Northwest of the US leave a considerable volume of unused woody biomass in the forest in the form of treetops and branches. These harvest residues are generally collected into slash piles and treated as part of a regional forest fire mitigation mandate. The activities of burning the non-merchantable material are designed to prevent the greater release of emissions through wildfire (Oneil and Lippke, 2010) which would occur if large amounts of residuals are left in forest. The predominant method for most private and land managers is to pile and burn the material. On national forest lands piling and burning are used on gentle slope and broadcast burning on steep slope (Oneil and Lippke, 2010). Slash pile burning releases the carbon sequestered in the woody biomass into the air in form of carbon dioxide (CO<sub>2</sub>) with potential impact on global warming. Moreover conducting broadcast burns is labor intensive and time consuming, and they substantially increase forest management costs.

Removing the harvest residuals from forest greatly reduces the need for slash pile burning with the consequence of substantially reducing the emissions that are generated from it.

Despite the potential environmental benefits of using these residuals, the economic feasibility of

extracting them from the forest is limited due to low market demand and high collection and transportation costs. To address the market failure of more fully utilizing woody residues, the NARA Project is exploring the economic and environmental feasibility of converting residual woody biomass into iso-paraffinic kerosene (IPK) bio-jet fuel.

The use of clean renewable fuels has been encouraged since the Energy Independence and Security Act was signed into law in 2007, providing meaningful economic opportunity for the reduction of foreign oil dependence and greenhouse gas emissions. The US Energy Information Administration (EIA) requires that the overall greenhouse gas emissions of cellulosic bio-fuel produce 60% lower carbon emissions relative to jet fuel produced from fossil fuel in order to be eligible for public procurement. It has been suggested that the replacement of fossil fuels with biofuels from wood resources that are currently wasted or are not of adequate quality to produce products can substantially reduce emissions (Lippke et al., 2012). The use of residual material as a bioenergy feedstock to produce bio-fuel not only would greatly decrease the level of emissions from burning activities but would also provide an important reduction in the fossil fuel use.

To estimate the overall environmental impact associated with recovering woody biomass to produce bio-jet fuel, as well as any net reduction in emissions to the atmosphere associated with avoiding the use of fossil fuel, a comprehensive Life Cycle Assessment (LCA) is the internationally recognized method.

Life Cycle Assessment (LCA) is a methodology to assess the environmental impacts of a product or activity (a system of products) over its entire life cycle. LCA has evolved into an internationally accepted method for analyzing complex environmental impacts and outputs of a product (Puettmann et al., 2010b) . The most widely accepted methodologies are set forth in the International Organization for Standardization (ISO) 14000 series of standard (ISO, 2006a, 2006b). This study follows the ISO 14040 and 14044 protocol and Consortium for Research on renewable Industrial Materials (CORRIM) guidelines and format (CORRIM, 2001). Beginning in 2000 CORRIM published several wood product and forestry life-cycle inventories (LCIs). These extensive LCIs were the first publically available LCI studies covering US forestry and wood products that followed international standards (Puettmann et al., 2010a).

This research project is exploring the potential of converting woody biomass into bio-energy within the U.S. Inland West region assessing the environmental implications of producing woody biomass based bio-fuel through the following objectives:

1. Perform a detailed Life Cycle Assessment (LCA) to evaluate the environmental impacts of using woody biomass as a feedstock for conversion into bio-energy.
2. Incorporate the avoided environmental impacts associated with piling and burning the woody biomass within the forest into the LCA calculations.
3. Compare the environmental implications of the NARA bio-energy vs fossil fuel energy.

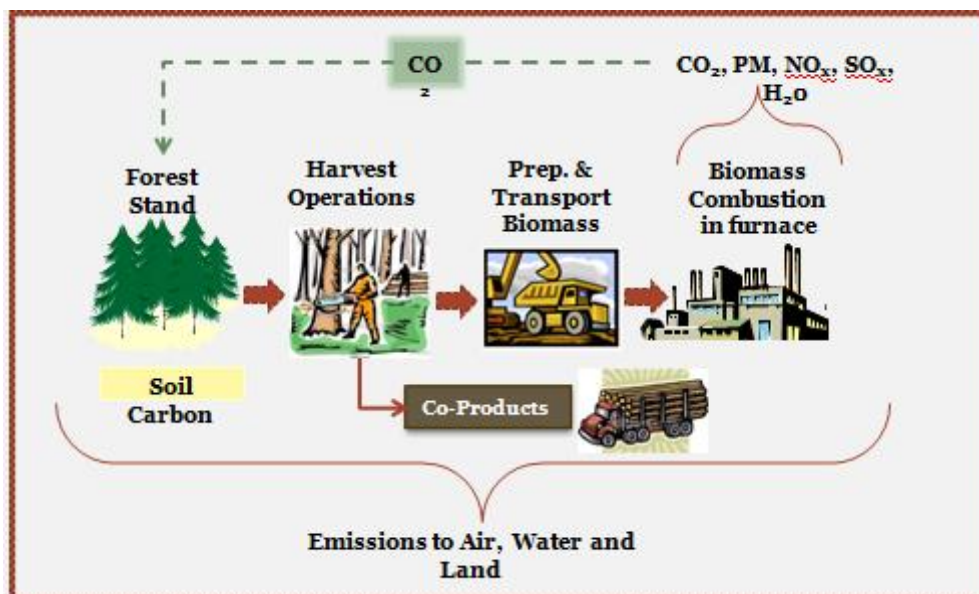


This research project is part of the NARA project, reducing the system boundary to feedstock, excluding the chemical processes to produce bio-jet fuel and burning the biomass to produce bio-energy.

## 5.5 Materials and methods

### 5.5.1 System boundary

A ‘cradle-to-grave’ life-cycle assessment of woody biomass-based bio-jet fuel was performed, where ‘cradle’ is defined as the natural forest regeneration of young trees and “grave” is defined as the biomass combustion. The environmental impacts were assessed using TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) indicator factors global warming, ozone depletion, photochemical smog, human toxicity potentials. As per IPCC Fifth Report, this paper will report the 100 year impact assessment numbers for the global warming potential (IPCC, 2013). The product system is wood chips whose function is to produce heat. The functional unit of the system is 1 MJ. A simplified diagram of the system boundaries associated with the wood chips life cycle is depicted in Figure 5.2.

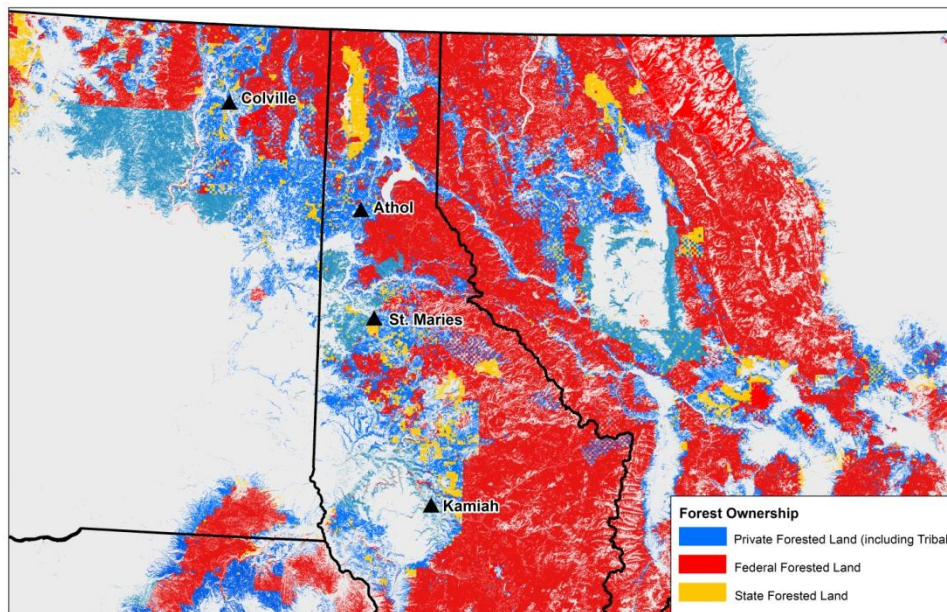


**Figure 5.2** System boundaries of the Life Cycle Assessment of wood chips.

As shown in the figure, the overall system boundary for developing the LCA of wood chips consists of the following components: (i) woody biomass collection and processing within the forest; (ii) feedstock logistics; (iii) biomass combustion and heat production. The individual components of the flow chart presented in Figure 1 are explained in greater detail in the following sections.

### 5.5.2 Woody Biomass Collection and Processing

Geographical location, regional vegetation, and topographical characteristics significantly affect the environmental impacts associated with harvesting, collecting and transporting the woody residues from the forest landing to the biomass processing facility. The species from which biomass was collected from in this study were mixed forests of ponderosa pine and lodgepole pine. Natural regeneration is the forest management scheme in this region, with little to no plantation or thinning operations being performed. With reference to the Pacific Northwest (PNW), LCA estimates for woody biomass collected from the interior west region (east of Cascades) is substantially different from the western Washington/Oregon region. Moreover, within the same sub-region, differences in LCA results might result from differences in forest management intensity and the type of forest management practices associated with different types of forest ownership (e.g., private vs state vs federal). This paper assesses the environmental implications of producing woody biomass within the eastern Washington, northern Idaho, and western Montana region.



**Figure 5.3** Regional Scope of Study (courtesy Natalie Martinkus)

The analysis also considers the harvest residue collected from private and state forests in Figure 5.3. The biomass resource from federal forests is not included in this analysis.

Based on the forest woody biomass models and empirical results, it is estimated that 61% of the above ground biomass harvested from a mature forest in the interior west region consists of sawlogs and pulp logs with the remaining 39% being composed of branches and tops (residual woody biomass). Woody biomass residuals carry low environmental burdens when compared to

standing timber that carries most of the environmental impacts from forestry operations (Sunde et al. 2011), whereas most of the impacts from residuals are from of extraction of residuals from the forest and transporting them to a pre-treatment facility. Haase et al., (2009) reported that CO<sub>2</sub> emissions from short rotation forestry biomass are 3 to 4 times higher than for forest residues. These residuals represent the feedstock for the project (Figure 5.2). However, a significant portion of the residuals ends up being scattered around the forest floor during the harvest and skidding operations. Based on empirical time-motion studies, it is estimated that 65% of the residuals gets collected into slash piles at the primary harvest landings. This research assumes that 10% of the biomass in the slash pile is left behind at the landing during the loading, chipping, and transporting of the biomass from the landing site to the biomass processing (pretreatment) facility. Based on these conditions, it is estimated that only 58.5% of the total harvest residuals generated during the timber harvest operation is delivered to the pre-treatment facility for conversion into biofuel.

Since residual woody biomass is generated during the harvest operation, and there are multiple products generated from the harvest operation (e.g., sawlogs, pulp logs and residuals), an allocation mechanism needs to be adopted to assign the environmental burdens associated with the production of each of the products. For this project, a “mass flow” allocation principle was adopted. Since 39% of the above-ground tree biomass is generally left in the forest as harvest residues following a logging operation (either on the forest floor or at harvest landing), a mass equivalent proportion (39%) of the environmental impacts associated with harvest activities is allocated to the woody biomass based feedstock LCA.

The data used in the SimaPro model are from CORRIM Phase I and CORRIM Phase II reports (Bowyer et al., 2004; Lippke et al., 2010).

The hourly fuel consumption of the machine *i* is evaluated through the following:

$$FC_i = FCR_i \cdot HP_i$$

$FC_i$  = hourly fuel consumption of the machine *i* [l/BDmT]

$FCR_i$  = fuel consumption rate of the machine *i* [l/HP/SMH]

$HP_i$  = horse power of the machine *i* [BDmT/SMH]

The lubricant consumption is evaluated from the fuel consumption through the following:

$$LC_i = FC_i \cdot ULC_i$$

$LC_i$  = lubricant consumption [l/BDmT]

$FC_i$  = fuel consumption [l/BDmT]

$ULC_i$  = lubricant consumption for unit of consumption of fuel ( $ULC_i = 0.018$ ).

**Table 5.2** Diesel and lubricants consumption of forest equipments (CORRIM database).

Outputs [1 hr]	Inputs	
	Diesel [l]	Lubricants [kg]
Delimber	21.20	0.37
Skidder grapple - Medium Crawler	19.50	0.21
Feller Buncher	20.29	0.35
Front Loader	19.26	0.34
Large Whole Tree Chipper at Central Landing	68.55	1.07
Shuttle: dump truck; primary to central	34.07	0.53
Idle Engine dump Truck	7.50	0.12
Idle Engine 120CY chip van	8.33	0.13
Transport Chips to Facility (120 CY chip van)	37.85	0.59

The time needed to process 1 BDmT of woody biomass is given by the reciprocate of the machine actual production rate (converting BDT to BDmT through the conversion factor 0.907BDT/BDmT):

$$T_{BDmT} = \frac{1}{APR_i}$$

$T_{BDmT}$  = time needed to process 1 BDmT of biomass [SMH/BDmT]

$APR_i$  = actual production rate of the machine i [BDmT/SMH]

The actual production rate of the machine i is:

$$APR_i = PPR_i \cdot ME_i$$

$APR_i$  = actual production rate of the machine i [BDmT/SMH]

$PPR_i$  = potential production rate of the machine i [BDmT/PMH]

$ME_i$  = machine efficiency [%]

**Table 5.3** Inputs and outputs of the harvesting process.

Outputs				Inputs		
Residuals from forest harvest	1	ton	39%	Feller Buncher	0.04	hr
Sawlogs from forest harvest	1.51	ton	61%	Skidder grapple - Medium Crawler	0.14	hr
				Delimber	0.13	hr
				Wood, soft, US PNW, standing/m3	3.51	m3

### 5.5.3 Feedstock Logistics

The transportation and in-woods processing/handling of the woody biomass can significantly influence the overall environmental performance of the woody feedstock. Location, slope conditions, and ease of access of forest biomass supplied to biofuel plants is highly variable. Also size and distribution of material varies greatly (Johnson et al., 2012). Based on forest management practices, topography and existing road network in the inland west region, a series of woody biomass transportation scenarios are considered in this paper. Emissions generated and total energy used were calculated for each of the feedstock handling and transportation scenarios to identify the optimal solutions that minimized environmental burdens. A benchmark scenario, based on the most likely scenario in the region is presented in Table 5.4 Equipment configuration of the benchmark scenario. and Table 5.5.

**Table 5.4** Equipment configuration of the benchmark scenario.

Scenario	Harvest system	Loose residue shuttle (to secondary landing)	Chipper at central landing	Chip transportation to pre-treatment gate
Benchmark	Gentle slope; mechanized; (Feller Buncher, Track Skidder)	Modified dump truck (30 CY capacity)	Large chipper; direct loader	Chip van (120 CY capacity)

**Table 5.5** Benchmark scenario for road-type specific transportation distances.

Road type (Avg. miles/hr)	Spur road (6 mph)	1 ½ lane (20 mph)	Gravel (29 mph)	Highway (55 mph)	Interstate (62 mph)	Total
Benchmark One way haul miles	2.5	5	10	20	37.5	75

The harvest system and in-woods feedstock handling benchmark scenario are presented in **Errore. 'origine riferimento non è stata trovata.** The distance that the woody biomass must be carried from the harvest site to the processing facility on different types of roads is presented in **Errore. 'origine riferimento non è stata trovata.** 5.5. A “gentle slope mechanized harvest” system consists of a medium sized feller buncher and a track skidder for moving the harvested whole trees to the landing site. Within the benchmark scenario, the loose residues are transported from the primary landing to the secondary landing in a 30 cubic yard (CY) dump truck, where they are chipped using a large chipper. In this scenario, the residuals must be transported from the primary landing to the secondary landing where the chipper and direct loader are located because the 120 CY chip vans cannot navigate the forest spur road. The chipped residues are directly loaded into a 120 CY chip van and transported to the pretreatment facility. Grinding and chipping results were not readily available until Harrill (2010) ran time motion studies to measure the productivity of these

machines. Within the benchmark scenario the total distance from the primary landing to the biomass processing facility is 75 miles.

Multiple scenarios are developed to test the impact of different transportation logistics on the overall LCA.

The alternate equipment scenario (Alt. Equip 1) presented in Table 5.6 assumes that the forest road between the primary landing and the secondary landing can accommodate a 50 CY roll-off container to shuttle loose residuals between the primary landing and the central landing, rather than the baseline 30 CY dump truck used in the baseline scenario.

**Table 5.6** Equipment configuration of the alternate scenarios.

Scenario	Harvest system	Loose residue shuttle (to secondary landing)	Chipper at central landing	Chip transportation to pre-treatment gate
Alt. Equip 1	Same as Benchmark	Roll-off container (50 CY capacity)	Same as Benchmark	Same as Benchmark

The first alternate transportation scenario (Alt. Trans. 1) presented in Table 5.7 assumes that the primary landing is alongside a 1½ lane road (e.g., 0 miles spur road) where the residual processing equipment (e.g., large chipper and direct loader) and the 120 CY chip vans can be brought in to the primary landing and a centralized secondary landing is not required.

**Table 5.7** Alternate scenarios for road-type specific transportation distances.

	Road type (Avg. road speed)	Spur road (6 mph)	1.5 lane (20 mph)	Gravel (29 mph)	Highway (55 mph)	Interstate (62 mph)	Total
Alt Trans 1	One way haul miles	0	5	10	20	40	75
Alt Trans 2	One way haul miles	5	5	10	20	35	75

The second alternate transportation (Alt. Trans. 2) scenario presented in Table 5.7 assumes that the distance between the primary landing and secondary landing is 5 miles of spur road. In this scenario, the residuals must be transported from the primary landing to the secondary landing where the chipper and direct loader are located because the 120 CY chip vans cannot navigate the forest spur road. The total distance from the primary landing to the pretreatment facility for both of the alternate scenarios has been kept constant at 75 miles.

The time required to transport 1 BDmT of woody biomass by the truck is evaluated by dividing the total cycle time of the truck  $i$  by its capacity (and eventually converting BDT to BDmT through the conversion factor  $0.907BDT/BDmT$ ):

$$T_{BDmT} = \frac{CT_i}{C_i}$$

$T_{\text{BDmT}}$  = time required to transport 1 BDmT of woody biomass by the truck [SMH/BDmT] (SMH = Standard Machine Hours)

$CT_i$  = total cycle time of the truck i [SMH]

$C_i$  = capacity of the truck i [BDmT]

The transportation time (shuttle or chip van) is evaluated considering the total travel time and setting the loading and the unloading times to zero. Conversely, the idle engine time refers to the loading and unloading times setting the total travel time to zero.

The total cycle time of the truck i is equal to the sum of the loading time, the travel time and the unloading time:

$$CT_i = LT_i + TT_i + UT_i$$

$CT_i$  = total cycle time of the truck i [SMH]

$LT_i$  = loading time of the truck i [SMH]

$TT_i$  = total travel time of the truck i [SMH]

$UT_i$  = unloading time of the truck i [SMH]

The total travel time of the truck i is the sum of the travel time on different roads (spur road, 1 ½ road, gravel, highway, interstate):

$$TT_i = \sum_{j=1}^n tt_{ij}$$

$TT_i$  = total travel time of the truck i [SMH]

$tt_{ij}$  = travel time of the truck i on the road j [SMH]

The travel time is obtained by dividing the distance covered by the average speed:

$$tt_{ij} = \frac{2 \cdot d_{ij}}{v_j} \cdot ME_i$$

$d_{ij}$  = distance covered by the truck i on the road j

$v_j$  = average speed on the road j

$ME_i$  = machine efficiency [%]

The data of the energy and material inputs are summarized in Table 5.8 and Table 5.9 when using respectively a 30 CY dump truck and a 50 CY roll off.

**Table 5.8** Energy and material consumption for 1 BDmT of wood chips, 30 CY dump truck.

<b>Dump truck (= 30 CY)</b>				
<b>Outputs</b>	<b>Unit</b>			
Wood chips	ton	1		
<b>Inputs</b>	<b>Unit</b>	<b>Benchmark</b>	<b>S1 (= 0 miles)</b>	<b>S2 (= 5 miles)</b>
Residuals from Forest Harvest	ton	1.111	1.111	1.111
Front Loader	hr	0.2166	0.217	0.217
Large Whole Tree Chipper at Central Landing	hr	0.020	0.020	0.020
Shuttle: dump truck (30CY); primary to central	hr	0.329	0	0.658
Idle Engine 30CY dump Truck	hr	0.369	0	0.369
Idle Engine 120CY chip van	hr	0.015	0.015	0.015
Transport Chips to Facility (120 CY chip van)	hr	0.180	0.185	0.175

**Table 5.9** Energy and material consumption for 1 BDmT of wood chips, 50 CY roll off.

<b>Roll off (= 50 CY)</b>				
<b>Outputs</b>	<b>Unit</b>			
Wood chips	ton	1		
<b>Inputs</b>	<b>Unit</b>	<b>Benchmark</b>	<b>S1 (= 0 miles)</b>	<b>S2 (= 5 miles)</b>
Residuals from Forest Harvest	ton	1.111	1.111	1.111
Front Loader	hr	0.217	0.217	0.217
Large Whole Tree Chipper at Central Landing	hr	0.020	0.020	0.020
Shuttle: dump truck (50CY); primary to central	hr	0.081	0.000	0.162
Idle Engine 50CY dump Truck	hr	0.279	0.000	0.279
Idle Engine 120CY chip van	hr	0.015	0.015	0.015
Transport Chips to Facility (120 CY chip van)	hr	0.180	0.185	0.175

#### **5.5.4 Biomass combustion and heat production**

Wood chips were assumed to burn in a 50 kW furnace to produce energy for heating. According to the European Biomass Association (AEBIOM, 2009), the oven-dry calorific values (NCV<sub>0</sub>) of different wood species varies within a very narrow interval, from 18.5 to 19 MJ/kg. Assuming a NCV<sub>0</sub> of 18.5MJ/kg, to produce 1MJ of energy 54g of oven-dry biomass is needed, i.e. 0.000054 BDmT.



### 5.5.5 Avoided impacts of slash piles burning

A common practice in forest operations in the Pacific Northwest is to collect a considerable volume of woody residuals, mainly constituted by treetops and branches, pile and burn them in the forest.



**Figure 5.4** Piling and burning woody residuals in forest is a common practice in the U.S. Pacific Northwest.

These fires can have potential impacts on the environment since they emit a variety of gases and aerosols to the atmosphere, including carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), oxides of nitrogen (NO<sub>x</sub>), volatile and semivolatile organic compounds (VOC and SVOC), particulate matter (PM), ammonia (NH<sub>3</sub>), sulfur dioxide (SO<sub>2</sub>) and methane (CH<sub>4</sub>) (Wiedinmyer et al. 2006).

The combustion of biomass produce non-methane organic compounds (NMOC), constituted by 1) Non-methane hydrocarbons (NMHC), which contain only C and H such as alkanes, alkenis, alkinis, aromatics and terpenes and 2) Oxygenated volatile organic compounds (OVOC), which contain C, H and O, such as alcohols, aldehydes, ketones and organic acids.

Significant amounts of nitrous acid (HONO), hydrocyanic acid (HCN) and acetonitrile (CH<sub>3</sub>CN) are also produced by fires.

Biomass in fires can burn in different ways:

1. Flaming combustion, which converts C, H, N and S into CO<sub>2</sub>, H<sub>2</sub>O, NO<sub>x</sub> and SO<sub>2</sub> and produces most of the black carbon particles;
2. Smoldering combustion, which, as fire progresses, tends to play a more dominant role via both surface oxidation (gasification) and pyrolysis and it produces most of CO, CH<sub>4</sub>, non-methane organic compounds (NMOC) and primary organic aerosol.

Flaming and smoldering combustion frequently occur simultaneously during a fire and distinct combustion phases may not occur. Smoldering is not caused by a deficiency of O<sub>2</sub> but can be affected by fuel geometry, growth stage, moisture, windspeed, etc (Akagi et al., 2010).

Gases emitted by the combustion in fires can affect air quality because they are responsible of the formation of global tropospheric ozone (O<sub>3</sub>). The O<sub>3</sub> is formed via the oxidizing power of the hydroxyl radical (OH) that is produced by photolysis of some oxygenated NMOC and O<sub>3</sub> and that reacts with the carbon monoxide and NMOC. Also nitrous acid (HONO) forms OH and NO via

photolysis and can be an important source of the OH radical, that initiates attack NMOC (Akagi et al., 2010). Furthermore woody biomass piles may sometimes cause more severe fires that can affect the carbon balance in forest.

Fire is a process that directly or indirectly releases carbon to the atmosphere as biomass is consumed (Hurteau and Brooks, 2011). The quantity of direct emissions is in part function of fire intensity. Net carbon is released by the forest during the combustion and immediately after the fire before vegetation is reestablished (post-fire decomposition), incorporating decomposition of materials that were created by the fire (e.g. dead tree boles) (Amiro et al., 2001).

Recovering woody residuals to produce bio-energy has the consequence of avoiding the emissions that would have been produced if no recovery occurred.

The combustion emissions have been evaluated from the data of percent distribution between unmerchantable stem and crown for residuals (CORRIM, 2001) (Table 5.10 **Errore. L'origine iferimento non è stata trovata.**) since they are characterized by different sizes.

**Table 5.10** Percent distribution between unmerchantable stem and crown for residuals (CORRIM, 2001)

Percent Distribution by Component	State and Private Forests			National Forest
	Piles	Moist Forest	Dry Forest	
Percent in Unmerchantable Stem	25.7%	25.7%	25.7%	64.6%
Percent in Crown	74.3%	74.3%	74.3%	35.4%

Different combustion phases occur by fuel size class, thus percent values have been extracted from the Consume 3.0 software (<http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml>) (Table 5.11).

**Table 5.11** Percent values of combustion phases for fuel class size (from Consume 3.0 software).

	Flame	Smolder	Residual	
0-1/4 inch	0.95	0.05	0.00	
1/4 - 1 inch	0.90	0.10	0.00	<i>Assumed for Crown</i>
1 - 3 inches	0.85	0.10	0.05	
3 - 9 inches	0.60	0.30	0.10	<i>Assumed for Stem</i>
9 - 20 inches	0.40	0.40	0.20	

A 1/4 – 1 inch class size was assumed for crown and a 3 – 9 inches class size for stem. The values of emissions have been weighted by the percent of flame and smolder for crown and stem for State and Private Dry Forests, the State and Private Moist and Cold Forests and the National Forests Dry-Moist-Cold Forests. Based on these values, fire emissions have been evaluated. (Battye and Battye, 2002; Prichard et al., 2006) The results are reported in Table 5.12-5.14.

**Table 5.12** Fires emissions estimation for State and Private Dry Forests.

<b>Ownership and Case</b>	<b>State and Private Dry Forests</b>				
<b>Residue Treatment</b>	Whole Tree	Whole Tree	Bole Only	Whole Tree	Bole Only
<b>Kilograms / Hectare</b>	Piled at Landing	Piled in Woods	Piled in Woods	Broadcast Burn	Broadcast Burn
Particulates (PM2.5)	106.51	53.25	170.41	138.92	277.84
Particulates (PM10)	120.14	60.07	192.22	155.23	310.46
Particulates - Total	184.90	92.45	295.85	234.13	468.26
CO	894	447	1,431	1,203	2,406
CO2 (Non Fossil)	22,679	11,339	36,286	32,328	64,655
Methane	62.64	31.32	100.23	49.15	98.31
Non Methane Hydrocarbons	55.61	27.80	88.97	45.34	90.68
VOC	76.02	38.01	121.63	102.26	204.51
Elemental Carbon	7.67	3.83	12.27	10.00	20.00
Organic Carbon	57.51	28.76	92.02	75.02	150.03
NOx	67.31	33.66	107.70	48.62	97.23
Ammonia	6.53	3.26	10.45	8.78	17.56
SO2	22.35	11.17	35.76	16.14	32.28
Methanol	8.85	4.43	14.17	11.91	23.82
Formaldehyde	14.31	7.15	22.89	19.25	38.50

**Table 5.13** Fires emissions estimation for State and Private Moist and Cold Forests.

<b>Ownership and Case</b>	<b>State and Private Moist and Cold Forests</b>				
<b>Residue Treatment</b>	Whole Tree	Whole Tree	Bole Only	Whole Tree	Bole Only
<b>Kilograms / Hectare</b>	Piled at Landing	Piled in Woods	Piled in Woods	Broadcast Burn	Broadcast Burn
Particulates (PM2.5)	128.38	64.19	205.42	167.46	334.92
Particulates (PM10)	144.82	72.41	231.71	187.12	374.23
Particulates – Total	222.89	111.44	356.62	282.23	564.46
CO	1,078	539	1,725	1,450	2,900
CO2 (Non Fossil)	27,337	13,669	43,740	38,969	77,937
Methane	75.51	37.76	120.82	59.25	118.50
Non Methane Hydrocarbons	67.03	33.52	107.25	54.65	109.31
VOC	91.63	45.82	146.61	123.26	246.52
Elemental Carbon	9.24	4.62	14.79	12.06	24.11
Organic Carbon	69.33	34.66	110.92	90.43	180.86
NOx	81.14	40.57	129.83	58.60	117.21
Ammonia	7.87	3.93	12.59	10.59	21.17
SO2	26.94	13.47	43.10	19.46	38.91
Methanol	10.67	5.34	17.08	14.36	28.71
Formaldehyde	17.25	8.62	27.60	23.20	46.40

**Table 5.14** Fires emissions estimation for National Dry-Moist-Cold Forests.

Ownership and Case	National Dry-Moist-Cold Forests				
Residue Treatment	Whole Tree	Whole Tree	Bole Only	Whole Tree	Bole Only
Kilograms / Hectare	Piled at Landing	Piled in Woods	Piled in Woods	Broadcast Burn	Broadcast Burn
Particulates (PM2.5)	191.91	95.96	307.06	270.30	540.59
Particulates (PM10)	217.12	108.56	347.40	298.63	597.27
Particulates – Total	319.50	159.75	511.20	435.30	870.60
CO	1,651	826	2,642	2,316	4,631
CO2 (Non Fossil)	36,411	18,205	58,257	91,097	103,454
Methane	121.55	60.78	194.48	101.24	202.47
Non Methane Hydrocarbons	98.56	49.28	157.69	84.72	169.44
VOC	140.35	70.18	224.57	196.83	393.67
Elemental Carbon	13.82	6.91	22.11	19.46	38.92
Organic Carbon	103.63	51.82	165.81	145.96	291.92
NOx	109.36	54.68	174.97	78.98	157.96
Ammonia	12.05	6.03	19.29	16.90	33.81
SO2	36.31	18.15	58.09	26.22	52.44
Methanol	16.35	8.17	26.16	22.93	45.85
Formaldehyde	26.42	13.21	42.27	37.05	74.10

The data of emissions collected have been used to model the burning process in Simapro v.3.2 and obtain the environmental impacts associated with them.

Site preparation for state and private lands was assumed to involve mechanized piling and burning using an excavator. Fuel consumption rates and emission factors were based on broadcast burning of slash disposal. They were developed from published studies that documented and modeled emission rates from both prescribed burns and wildfire (Battye and Battye, 2002; Oneil and Lippke, 2010; Prichard et al., 2006).

### ***5.5.6 Comparative Analysis: Global Warming Potential of wood chips vs firewood***

To compare the results of the two case studies it is necessary to consider that they were performed using two different LCA evaluation methods. The Italian case study was performed using the CML method while the U.S. Pacific Northwest case study was performed using TRACI.

Comparing impact categories which have an impact on local scale is critical. As outlined in Chapter 3, some impacts are evaluated by using site specific parameters. For example, in TRACI site specificity is available for many impact categories and in all cases a United States average value exists when the location is undetermined. Thus the evaluated impacts depend on site specificity, e.g. dispersion and meteorological factors, specific of the area where the chemicals are released. For this reason, only the Global Warming Potential will be compared. The methodology

for the evaluation of the impact on global warming, in fact, is, in both methods, based on the IPCC Global Warming Potentials.

To compare the two LCAs it is necessary to homogenize the system boundaries of the two studies. The single processes were aggregated in the LCA phases: tree felling, extraction, processing at landing, off-road transport, production, on-road transport and combustion.

	Firewood	Wood chips
Tree felling	Chainsaw (3.6 kW)	Feller buncher
Extraction	Tractor (67 kW)	Skidder grapple – medium crawler
Processing at landing	Chainsaw (3.6 kW)	Delimber Front loader
Off-road transport	Tractor	Shuttle: dump truck
Production	Saw and split	Large whole tree chipper
On-road transport	Truck	120 CY chip van
Combustion	Furnace (6 kW)	Furnace (50 kW)

**Figure 5.5** Comparison of the system boundaries.

The two case studies present different levels of forest mechanization. While the firewood production in Italy is characterized by a low mechanization level since the machines used for the operations in forest and landing are basically chainsaws and tractor, the wood chips production in the Pacific Northwest adopts a higher mechanization level. The tree felling is performed by means of a feller buncher and the extraction by a skidder grapple. The processing at landing includes the use of a delimber and front loader.

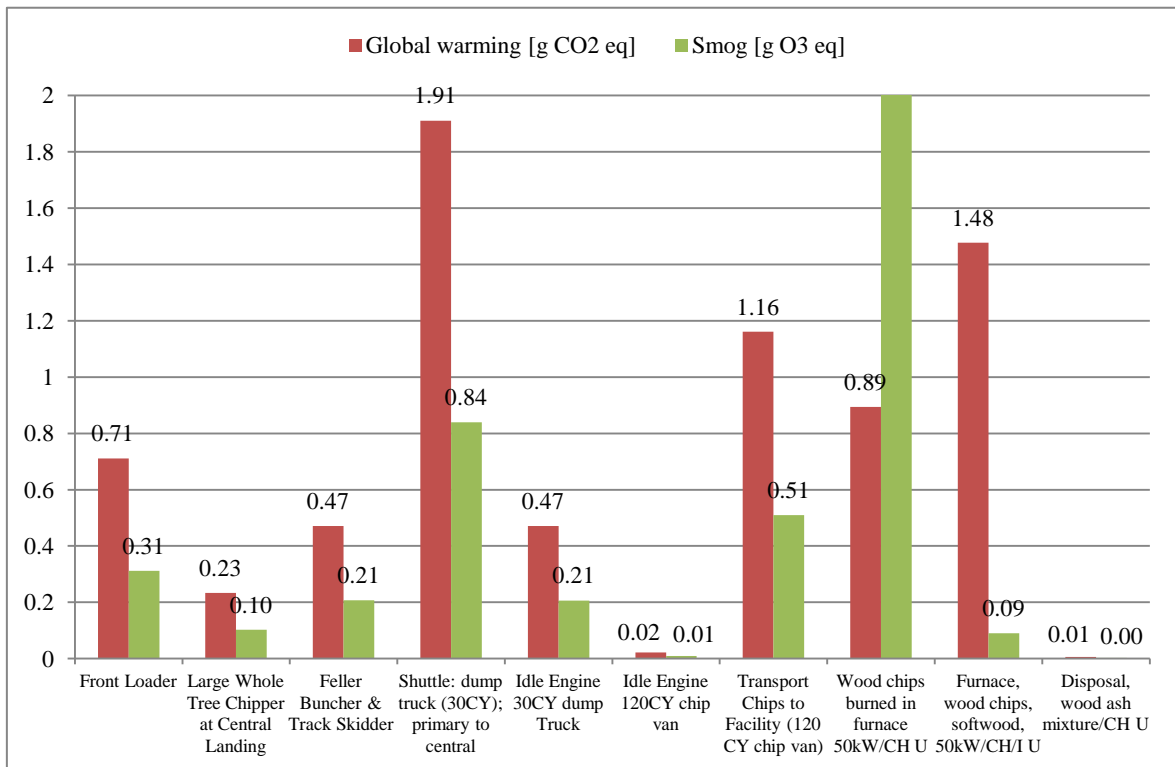
The production phase is also different since the two products present different characteristics. Firewood is produced by sawing and splitting while wood chips are produced by a whole tree chipper. The transportation means are different since the firewood supply chain includes the use of tractors for the extraction and for the off-road transportation. The wood chips supply chain includes the use of a skidder to extract wood from the forest and shuttle for the off-road transport. The transportation means for the on-road transport are comparable. However the consumption of fuel and lubricant are largely different between Europe and United States. The distribution phase, only present in the firewood LCA, was incorporated to the on-road transport phase, for a total of 50 km.

Lastly, the combustion occurs in furnaces of different power: 6 kW for firewood and 50 kW for wood chips.

## 5.6 Analysis and results

### 5.6.1 Results of the LCA of wood chips

Figure 5.6 shows the results of the LCA (combustion excluded) referred to 1 MJ of energy.



**Figure 5.6** Processes contribution to global warming, ozone depletion and photochemical smog potentials. The results are referred to 1 MJ of energy.

The results reveal that hauling forest residues over forest roads is the primary contributor to global warming potential (Figure 5.6).

Based on the previous LCA contribution analysis of the benchmark logistics scenario, it is evident that shuttling the loose residuals from the primary landing to the secondary landing is the major GWP contributor. Options to reduce the carbon footprint associated with loose residue collection may be critical in reducing the overall environmental burdens of the process. The results further reveal that strategic forest road development will reduce the global warming potential of feedstock collection over the long run.

Combining the benchmark scenario with the alternate equipment configuration and the alternate transportation scenarios allows us to test a total of six feedstock logistic scenarios (Table 5.15).

**Table 5.15** Alternate scenario for road-type specific transportation distances.

Equipment Scenario	Transportation Scenario	Scenario no.
Benchmark (30 CY Dump Truck)	Alt Trans 1 (no spur road)	A.1
	Benchmark (2.5 mile spur road)	B.1
	Alt Trans 2 (5 mile spur road)	C.1
Alt. Equip 1 (50 CY Container)	Alt Trans 1 (no spur road)	A.2
	Benchmark (2.5 mile spur road)	B.2
	Alt Trans 2 (5 mile spur road)	C.2

The first alternate transportation scenario (Alt. Trans. 1) does not require transporting the forest residuals on a spur road, and therefore the alternate equipment scenario (point A.1, Fig. 4) provided the same environmental impact as the benchmark scenario (point A.2).

The LCA results for six scenarios excluding the avoided impacts deriving from burning the slash piles are shown in Table 5.16.

**Table 5.16** LCA results for the six scenarios, referred to 1 MJ of energy.

		A1	A2	B1	C1	B2	C2
<b>Global warming</b>	g CO <sub>2</sub> eq	5.00	7.36	9.24	5.80	6.24	
<b>Smog</b>	g O <sub>3</sub> eq	3.83	4.87	5.69	4.18	4.38	
<b>Acidification</b>	mmol H <sup>+</sup> eq	6.73	8.57	10.04	7.36	7.70	
<b>Eutrophication</b>	mg N eq	9.75	11.69	13.25	10.40	10.77	
<b>Carcinogenics</b>	10 <sup>9</sup> CTUh	0.33	0.37	0.39	0.34	0.35	
<b>Non carcinogenics</b>	10 <sup>9</sup> CTUh	23.86	24.20	24.47	23.98	24.04	
<b>Respiratory effects</b>	g PM <sub>10</sub> eq	0.06	0.07	0.07	0.06	0.07	
<b>Ecotoxicity</b>	10 <sup>3</sup> CTUe	26.06	32.49	37.64	28.23	29.44	
<b>Ozone depletion</b>	mg CFC11	0.11	0.11	0.11	0.11	0.11	

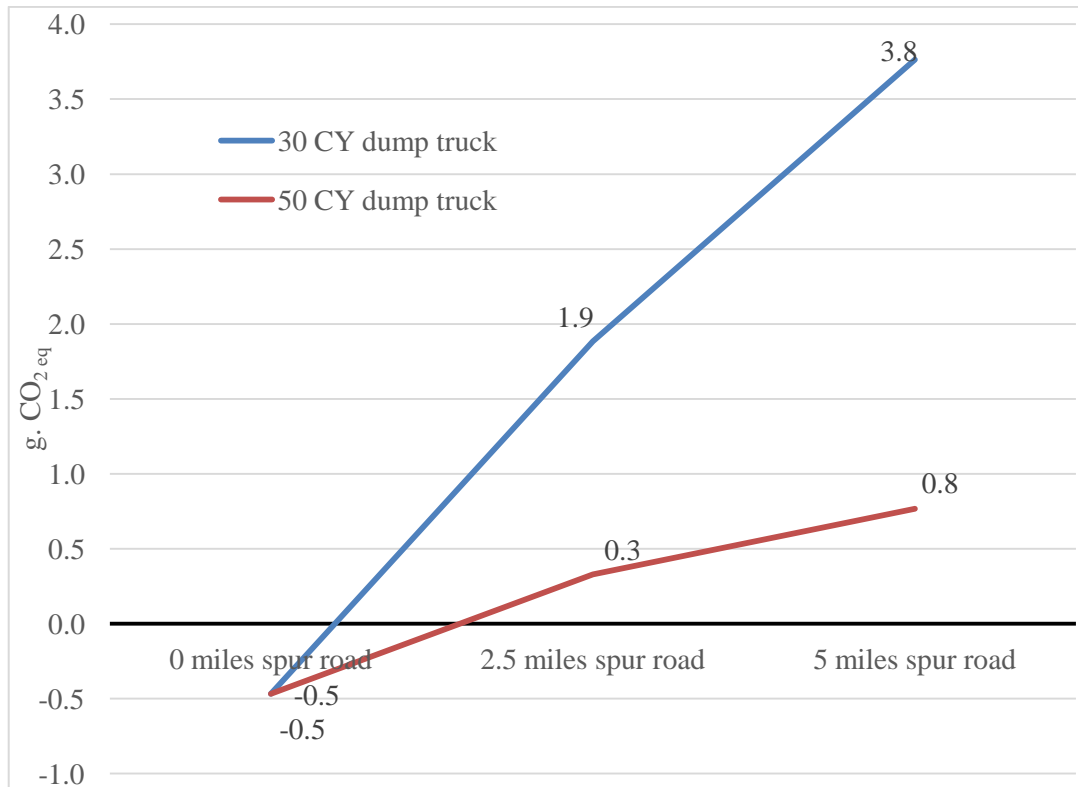
### 5.6.2 Avoided Environmental Burdens of Slash Pile Burning

The avoided environmental impacts derived from recovering residuals to produce bio-jet fuel feedstock rather than burning them in slash piles are substantial.

After factoring in the avoided environmental burdens of slash pile burning, the total carbon footprint of the baseline scenario using a 30 cubic yard container (point B.1 in Fig. 5.23) was 1.9 grams of CO<sub>2</sub> per 1 MJ of bioenergy produced. The environmental impact associated with scenarios A.1 and A.2, where the primary landing is located along a 1½ lane road and no spur road transportation is required, was negative for both scenarios (points A.1 and A.2). Using the larger 50 cubic yard container to haul the residuals 2.5 miles and 5 miles along a forest spur road (points B.2

and C.2, respectively) substantially reduced the global warming impacts relative to using the 30 CY dump truck.

The results presented in the Table 5.17 were developed using the baseline feedstock logistics scenarios presented in **Errore. L'origine riferimento non è stata trovata.**-5.7.



**Figure 5.7** Global warming potential of alternate feedstock scenarios for 1 MJ of energy.

The results show that the avoided greenhouse gas (GHG) emissions from slash pile burning substantially reduce the total GHG emissions from woody feedstock collection and transportation, resulting in a 42.1% reduction of the global warming potential value. Similarly, there is a net reduction in the total impact for the other environmental factors (smog formation, acidification, eutrophication, carcinogenics and respiratory effects). It should be noted that the large quantity of biogenic CO<sub>2</sub> emitted during the slash pile burning was not included in the analysis as per ISO and EPA guidelines.

The results show that after accounting for the avoided emissions from burning the residuals in slash piles, the overall LCA has net beneficial impacts on the three highlighted impact categories: acidification, carcinogenics and respiratory effects (denoted by net reduction).



**Table 5.17** *Net LCA results for the benchmark scenario including avoided impact.*

		Contribution from		
		Total impact	Avoided impacts	Net impact
<b>Global warming</b>	g CO2 eq	7.36	3.10	4.26
<b>Smog</b>	g O3 eq	4.87	4.61	0.26
<b>Acidification</b>	mmol H+ eq	8.57	9.08	-0.51
<b>Eutrophication</b>	mg N eq	11.69	8.05	3.64
<b>Carcinogenics</b>	10 <sup>9</sup> CTUh	0.37	0.65	-0.28
<b>Non carcinogenics</b>	10 <sup>9</sup> CTUh	24.20	0.01	24.19
<b>Respiratory effects</b>	g PM10 eq	0.07	0.59	-0.53
<b>Ecotoxicity</b>	10 <sup>3</sup> CTUe	32.49	1.31	31.19
<b>Ozone depletion</b>	mg CFC11	0.11	0.00	0.11

### ***5.6.3 Comparison of the results of the two case studies in terms of Global Warming Potential***

The results of the two case studies are compared in Figure 5.8. Although the two LCA studies were separately and independently performed, the results are coherent.

If no slash piles are considered, the results of the scenarios of the LCA of wood chips are included in the interval of the results of the two scenarios of the LCA of firewood.

If slash piles are considered, only the scenario C.1 has higher impact on climate change than the scenario “short chain” of the firewood LCA while all the other scenarios have lower impact.

The contribution of each phase of the LCA, as listed in the simplified scheme of Figure 5.5, are shown in Figure 5.9 and 5.10 respectively for the short and the long firewood supply chain and compared to the process contribution of the LCA of wood chips.

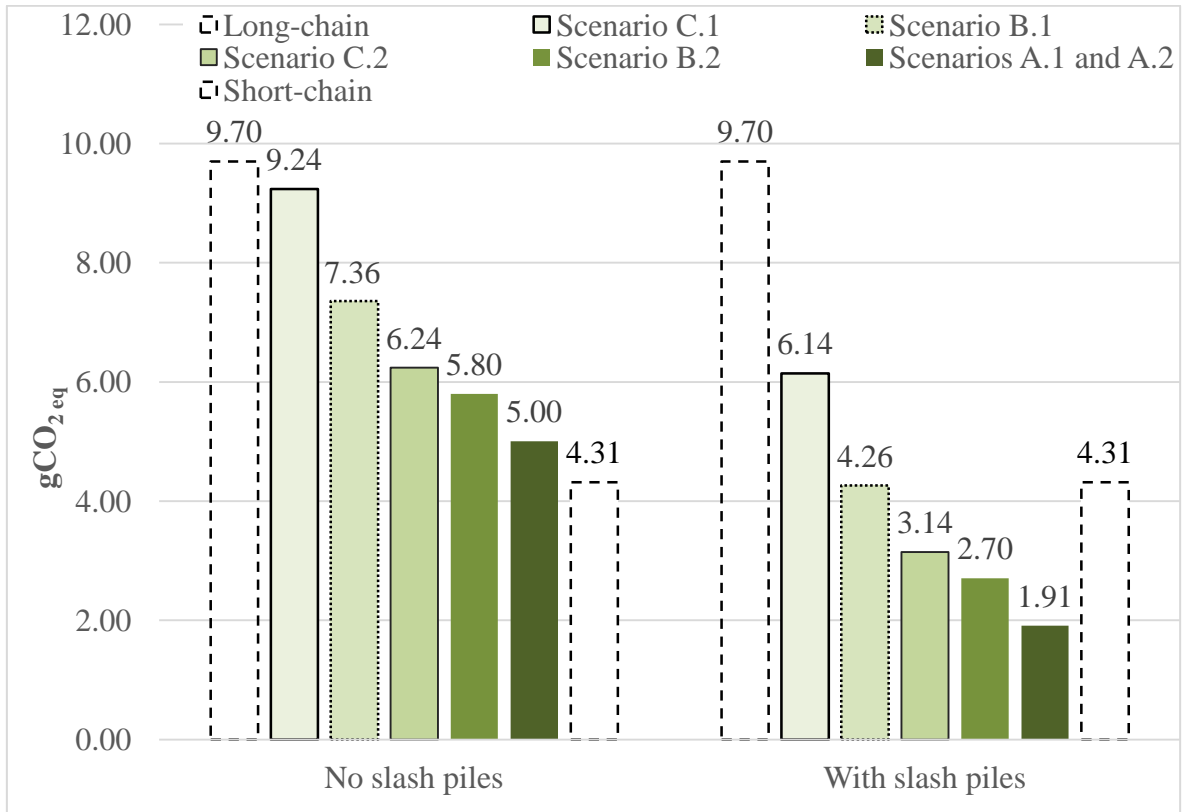


Figure 5.8 LCA results comparison excluding the avoided impacts from slash piles (left) and including them (right).

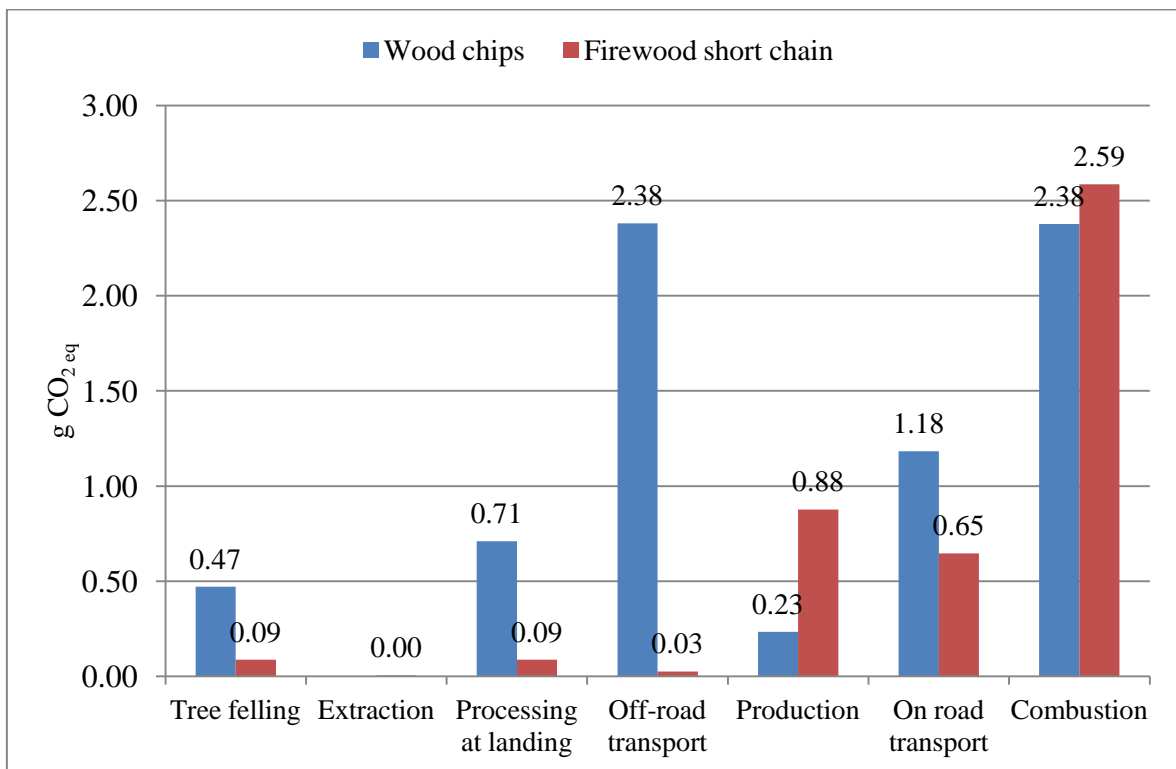
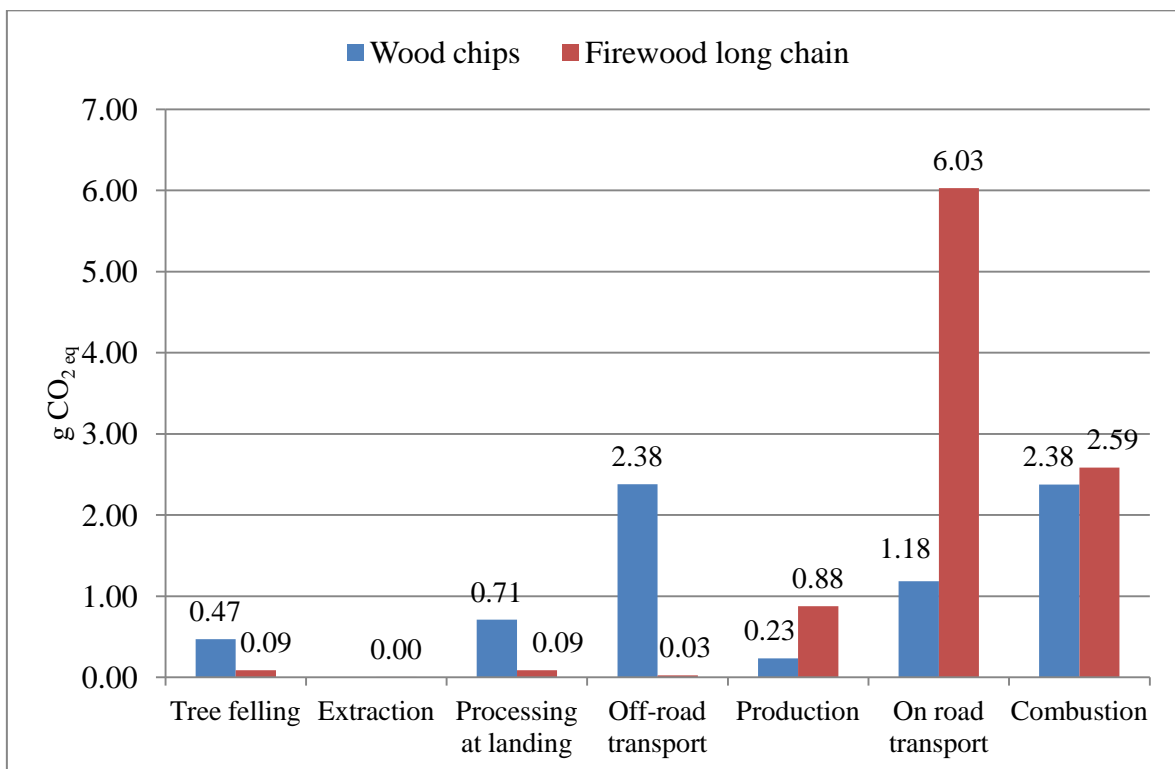


Figure 5.9 Comparison of the process contribution of the LCA of wood chips (benchmark scenario) and the LCA of firewood (short supply chain).

It is possible to observe that the contribution of tree felling and processing at landing are bigger in the wood chips than to the firewood LCA, due to the higher level of mechanization of the former, which includes the use of feller buncher, skidder, delimeter and front loader. Excluding the combustion phase, the length of the supply chain is the dominant factor in the carbon footprint of wood products for bio-energy.

Figure 5.9 highlights the importance of reducing the impact of the off-road transport. Travelling a spur road is energy intensive and variable depending on the morphology of the site, the slope, the speed and is a key contributor in the overall LCA of wood chips.



**Figure 5.10** Comparison of the process contribution of the LCA of wood chips (benchmark scenario) and the LCA of firewood (short supply chain).

Comparing the results of the short and the long supply chain, it is possible to observe that the contribution of the on-road transport emissions to the overall carbon footprint passes from 14.96% to 62.17% (distribution phases included).

## 5.7 Conclusions

Results obtained indicate that transportation of loose residue in the forest road contributes significantly to the overall carbon footprint of woody feedstock. Forest road conditions, limiting use of trucks with higher load carrying capacity to the primary landing, makes the feedstock

logistics more carbon intensive. Scenario C.1 presented in this paper has the largest GWP number and involves 5 miles spur road (between primary and secondary landing) inaccessible for larger roll-off containers. For Pacific Northwest, this condition can be considered an extreme condition and should be left outside the purview of feedstock collection zones. The results clearly suggest that it may be environmentally viable to broaden the resource zone rather than going very deep in the forest to collect the residual woody biomass. The avoided environmental impacts derived from recovering residuals rather than burning them in slash piles proved to be substantial. The results show that, for some of the scenarios discussed, residual biomass recovery operations can be conducted with no or minimal adverse global warming impact, using the avoided environmental impacts analysis. There are beneficial impacts in the three other categories of acidification, carcinogenics and respiratory effects as opposed to burning residuals in slash piles.

Comparing the results of the firewood and wood chips case studies, it is possible to conclude that, excluding biogenic carbon, the transportation logistic is the critical phase for both the supply chains. The contribution of biogenic carbon has been excluded recommended by LCA guidelines. In Part II of this dissertation it will be shown how to evaluate carbon sequestration and incorporate it in the LCA framework.

## **PART II**

### **Dynamic Life Cycle Assessment**



# Chapter 6

## Carbon sinks and stocks evaluation

Part I of this dissertation highlighted the main factors affecting the Life Cycle Assessment of wood products for bio-energy. Biogenic carbon plays a huge role in the impact on Global Warming. However in traditional LCA it is not accounted because it is assumed equal to the carbon sequestered from the atmosphere for trees growth. In this chapter the carbon sequestration has been evaluated. As for the LCA case studies, two areas of study have been considered for the evaluation of carbon sequestration: the Italian Alps and the U.S. Pacific Northwest.

### 6.1 Introduction

Carbon sequestration plays an important role in the life cycle assessment of forest products. The carbon cycle starts with the absorption of carbon dioxide from the atmosphere by trees through photosynthesis and its transformation in biomass for their growth. A fraction of the carbon absorbed is then returned to the atmosphere through the respiration and in part for disturbances (e.g. fire). Fires include not only CO<sub>2</sub> emission but also N<sub>2</sub>O, CH<sub>4</sub>, NO<sub>x</sub>, NMVOC and CO.

Some biomass is then transferred to dead organic matter pools (i.e. dead wood and litter) some of which decomposes quickly, returning carbon to the atmosphere, some remains stored for a long time.

When dead organic matter is decomposed it is then transformed into soil organic matter which is composed either of labile compounds that quickly release carbon to the atmosphere and recalcitrant compounds that are very slowly decomposed and can be retained in the soil for centuries.

Thus, some of the carbon removed from the ecosystem is rapidly emitted to the atmosphere while some carbon is transferred to other stocks, i.e. wood products which can store carbon in use and in landfill for years to centuries.

### 6.2 Materials and methods

According to the IPCC Guidelines for National Greenhouse Gas Inventories the following carbon pools should be taken into account (IPCC, 2006):

- Aboveground biomass: all biomass of living vegetation above the soil, including stems, stumps, branches, bark, seeds and foliage;
- Belowground biomass: all biomass of live roots with diameters larger than (suggested) 2 mm.
- Dead wood: all non-living woody biomass not contained in the litter, larger than or equal to

10 cm in diameter;

- Litter: all non-living biomass with a size greater than the limit for soil organic matter (suggested 2 mm) and less than the minimum diameter chosen for dead wood (e.g. 10 cm), lying dead, in various states of decomposition above or within the mineral or organic soil.
- Soil organic matter: live and dead fine roots and dead organic matter within the soil that are less than the minimum diameter limit (suggested 2 mm).

In this study the carbon sequestration from the aboveground biomass has been taken into account. The belowground biomass is explicitly excluded from the study while the decay of residues (top and branches) has been modeled for the US case study.

According to the IPCC Guidelines for National Greenhouse Gas Inventories carbon sequestration can be evaluated through a carbon stock change method (IPCC, 2006):

$$\Delta C_{LU} = \sum_i \Delta C_{LU_i}$$

$\Delta C_{LU}$  = carbon stock changes for a land-use category (i.e. forest land)

i = specific stratum or subdivision within the land-use category.

The carbon sequestered by the forest over the time can be evaluated, based on the Stock-Difference Method, as the difference of carbon stocks between time  $t_1$  and time  $t_2$  divided by the time frame:

$$\Delta C = \frac{(C_{t_2} - C_{t_1})}{(t_2 - t_1)}$$

$\Delta C$  = annual carbon stock change in the pool, tonnes C yr<sup>-1</sup>

$C_{t_1}$  = carbon stock in the pool at time  $t_1$ , tonnes C

$C_{t_2}$  = carbon stock in the pool at time  $t_2$ , tonnes C

The total carbon in biomass at time t is given by the following:

$$C = \sum_{i,j} \{A_{i,j} \cdot V_{i,j} \cdot BCEF_{S_{i,j}} \cdot (1 + R_{i,j}) \cdot CF_{i,j}\}$$

C = total carbon in biomass at time  $t_1$  and  $t_2$

A = area of land remaining in the same land-use category, ha

V = merchantable growing stock volume, m<sup>3</sup> ha<sup>-1</sup>



i = ecological zone i

j = climate domain j

R = ratio of below-ground biomass to above-ground biomass

CF = carbon fraction of dry matter, tonne C

BCEF<sub>s</sub> = biomass conversion and expansion factor for expansion of merchantable growing stock volume to above-ground biomass. BCEF<sub>s</sub> transforms merchantable volume of growing stock directly into its above-ground biomass (Table 4.5 IPCC 2006).

The amount of CO<sub>2</sub> which was absorbed from the atmosphere and converted in biogenic carbon can be evaluated by multiplying the amount of carbon by the molecular weight of CO<sub>2</sub> and divided by the molecular weight of carbon:

$$CO_2 = C \cdot \frac{MW_{CO_2}}{MW_C}$$

C = total carbon in biomass

MW<sub>CO<sub>2</sub></sub> = molecular weight of CO<sub>2</sub> (44 kg/kmol)

MW<sub>C</sub> = molecular weight of C (12 kg/kmol)

Carbon sinks may be partially compromised if the forest is subject to disturbance. Thus, where data were available, a buffer has been considered to take into consideration the possibility that a disturbance occurs. Only data about disturbance for the Italian case study were available which considered the three different types of natural disturbance:

- risk of the spread of fires;
- risk of parasite attacks;
- risk of breakage.

Data for the disturbance elaborated within the Carbomark Project have been used (Progetto Carbomark, 2011). For each forestry category the magnitude of the event with return time of 30 years has been determined, using extreme distribution.

## 6.3 Areas of the study

### 6.3.1 Italian Alps.

The first area of study (Figure 4.1) is represented by The Italian Alps where different case studies have been considered.

Eastern Alps:

- Veneto Region: 19 case studies in Province of Vicenza and Belluno
- Autonomous Province of Trento: case studies of Lavarone and Folgaria

Western Alps:

- Piemonte Region: case study of Val Varaita.



Figure 6.1 Area of study of Italian Alps.

Data for the case studies in Veneto Region have been elaborated starting from some previous data connected within the Carbomark Project ([www.carbomark.org](http://www.carbomark.org)).

Data from the case studies in Autonomous Province of Trento have been collected within a research agreement with CSQA (from Feb 15<sup>th</sup> until Dic 31<sup>st</sup> 2012).

Data from the Piemonte Region have been collected within a research agreement with IPLA.

### **6.3.2 US Pacific Northwest.**

The second area of study has been considered within the internship at the University of Washington (started on May 13<sup>th</sup> 2013 and ongoing).

The NARA study encompasses different areas of Pacific Northwest, Southeast and Inland West. The woody biomass collected in different regions leads to different results in the LCA due to differences in forest management intensity or the type of forest ownership so a sub-region specific analysis has been conducted based on the existing forestry and management practices used in the supply region associated with the location of the pretreatment facility.

The area of study, represented in Figure 6.1 considered is the Western Montana Corridor (WMC) that covers an area of 223 ha encompassing the Western half of the state and parts of northern Washington and Idaho. Data from the CORRIM database have been used.

## **6.4 Case studies:**

### **6.4.1 .Italian Alps**

The following case studies have been considered.

- Veneto Region: 19 case studies in Province of Vicenza and Belluno
- Autonomous Province of Trento: case studies of Lavarone and Folgaria
- Piemonte Region: case study of Val Varaita.

The selection of case studies has been carried out by sending surveys to a large number of municipalities and collecting the data from those one that showed interest.

All the forests considered in the Italian area of study are State Forests, for which official data are available in Forest Management Plans. The Private Forests have been explicitly excluded from the study for the lack of official information about the variables of interest.

The Forest Management Plan is a detailed operational planning of the individual property and contains complete information on the territory with regard to the evolution dynamics of the aboveground as well as detailed indications are provided concerning the planning of silvicultural interventions.

From ongoing Forest Management Plans data regarding the forest area, the volume of biomass, the average growth, the harvest/growth ratio, the type of species and their composition have been collected for all the case studies considered. The timeframe of the Forest Management Plan used in this study is 10 years, with the exception of the one considered for the Piemonte Region Plan for which it is 15 years. The rotation period is 75 years.

### 6.4.1.1 Veneto Region

In Veneto Region 11 municipalities in Province of Vicenza and 8 in Province of Belluno have been considered.

All the data used for the evaluation have been taken from their ongoing Management Plans. Data have been collected at level of single property, then average values of the factors have been evaluated for each municipality and they are shown in the following tables.

As shown in the following table for the Vicenza Province an overall area of 15199 ha has been considered including the municipalities of Luisiana, Valstagna, Caltrano, Roana, Asiago, Conco, Gallio, Cismon, Rotzo, Enego and Foza. The average volume in forest is 259 m<sup>3</sup> ha<sup>-1</sup> and the average biomass growth is 6.23 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>. The total harvest volume (17986 m<sup>3</sup> yr<sup>-1</sup>) divided by the total biomass growth (93478 m<sup>3</sup> yr<sup>-1</sup>) leads to an average harvest/growth ratio of 23.36%.

**Table 6.1** Summary of some data collected for the Vicenza Province in Veneto Region.

Num	Name	Area [ha]	Volume in forest [m <sup>3</sup> ha <sup>-1</sup> ]	Biomass Growth [m <sup>3</sup> yr <sup>-1</sup> ]	Biomass Growth [m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> ]	Harvest /Growth %	Harvested volume [m <sup>3</sup> yr <sup>-1</sup> ]
1	Comune di Lusiana	1230	246	6310	5.13	20.14%	1271
2	Comune di Valstagna	150	300	1150	7.66	79.40%	913
3	Comune di Caltrano	633	263	3218	5.08	14.31%	461
4	Comune di Roana	3795	263	21522	5.67	22.53%	4849
5	Comune di Asiago	2717	284	19138	7.04	19.06%	3648
6	Comune di Conco	85	207	557	6.57	20.37%	114
7	Comune di Gallio	1536	282	10320	6.72	12.32%	1271
8	Comune di Cismon	897	247	5104	5.69	17.10%	873
9	Demanio di Rotzo	1224	277	9687	7.92	25.16%	2437
10	Comune di Enego	1668	262	10632	6.37	12.44%	1323
11	Comune di Foza	1264	221	5841	4.62	14.16%	827
<b>Total</b>		<b>15199</b>		<b>93478</b>			<b>17986</b>
<b>Average</b>			<b>259</b>		<b>6.23</b>	<b>23.36%</b>	

**Table 6.2** Summary of some data collected for the Belluno Province in Veneto Region.

Num	Name	Area [ha]	Volume in forest [m <sup>3</sup> ha <sup>-1</sup> ]	Biomass Growth [m <sup>3</sup> yr <sup>-1</sup> ]	Biomass Growth [m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> ]	Harvest /Growth %	Harvested volume [m <sup>3</sup> yr <sup>-1</sup> ]
1	Regola di Santo Stefano	627	349	3576	5.70	67.46%	2413
2	Regole di San Vito di Cadore	410	311	2328	5.68	58.62%	1365

3	Magnifica regola grande dei Monti di Vodo	887	321	5182	5.84	42.68%	2212
4	Regola staccata di vodo di Cadore	232	254	856	3.69	86.12%	737
5	Domegge	1663	302	7957	4.78	23.79%	1893
6	Lorenzago	772	304	5619	7.28	35.95%	2020
7	Regola di San Pietro	256	345	1534	6.00	45.08%	692
8	Comune di Mel	301	300	3079	10.24	23.87%	735
<b>Total</b>		<b>5147</b>		<b>30131</b>			<b>12066</b>
<b>Average</b>			<b>311</b>		<b>6.15</b>	<b>47.95%</b>	

For the Belluno Province an overall area of 5147 ha has been considered including Regola di Santo Stefano, Regole di San Vito di Cadore, Magnifica Regola grande dei Monti di Vodo, Regola staccato di Vodo di Cadore, Domegge, Lorenzago, Regola di San Pietro e Comune di Mel. The average volume in forest is 311 m<sup>3</sup> ha<sup>-1</sup> and the average biomass growth is 6.15 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>. The total harvest volume (12066 m<sup>3</sup> yr<sup>-1</sup>) divided by the total biomass growth (30131 m<sup>3</sup> yr<sup>-1</sup>) leads to an average harvest/growth ratio of 47.95%.

#### 6.4.1.2 Autonomous Province of Trento

In Autonomous Province of Trento the case studies of Lavarone and Folgaria have been considered for an overall area of 2734 ha.

The average volume in forest is 333 m<sup>3</sup> ha<sup>-1</sup> and the average biomass growth is 6.88 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>. The total harvest volume is 10900 m<sup>3</sup> yr<sup>-1</sup> and the total biomass growth is 30131 m<sup>3</sup> yr<sup>-1</sup> leading to an average harvest/growth ratio of 58.23%.

In Comune di Folgaria the composition of species is 74,80% spruce, 19,50% fir, 3,70% larch, 0,74% Scots pine, 1,20% beech e 0,8% other hardwood while in Comune di Lavarone it is: 52,95% spruce, 40,11% fir, 1,07% larch, 0,74% Scots pine, 4,56% beech e 0,57% other hardwood.

**Table 6.3** Summary of some data collected for the Autonomous Province of Trento.

Num	Name	Area [ha]	Volume in forest [m <sup>3</sup> ha <sup>-1</sup> ]	Biomass Growth [m <sup>3</sup> yr <sup>-1</sup> ]	Biomass Growth [m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> ]	Harvest /Growth %	Harvested volume [m <sup>3</sup> yr <sup>-1</sup> ]
1	Comune di Folgaria	2016	346	13742	6.82	58.22%	8000
2	Comune di Lavarone	718	320	4976	6.93	58.23%	2900
<b>Total</b>		<b>2734</b>		<b>18718</b>			<b>10900</b>
<b>Average</b>			<b>333</b>		<b>6.88</b>	<b>58.23%</b>	

### 6.4.1.3 Piemonte Region

The case study of Val Varaita has been considered including the municipalities of Sampeyre and Frassino. The area is 877 ha, the average volume in forest is 293 m<sup>3</sup> ha<sup>-1</sup> and the average biomass growth is 5.45 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>. The total harvest volume is 3049 m<sup>3</sup> yr<sup>-1</sup> and the total biomass growth is 4344 m<sup>3</sup> yr<sup>-1</sup> leading to an average harvest/growth ratio of 70.20%.

**Table 6.4** Summary of some data collected for the Val Varaita in Piemonte Region.

Num	Name	Area [ha]	Volume in forest [m <sup>3</sup> ha <sup>-1</sup> ]	Biomass Growth [m <sup>3</sup> yr <sup>-1</sup> ]	Biomass Growth [m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> ]	Harvest /Growth %	Harvested volume [m <sup>3</sup> yr <sup>-1</sup> ]
1	Val Varaita	877	293	4344	5.45	70.20%	3049
<b>Total</b>		<b>877</b>		<b>4344</b>			<b>3049</b>
<b>Average</b>			<b>293</b>		<b>5.45</b>	<b>70.20%</b>	

## 6.5 Results

Results are summarized in the following tables.

**Table 6.5** Results of forest carbon sequestration evaluation for some municipalities in Vicenza Province in Veneto Region.

Num	Name	CO <sub>2</sub> sequestration NO BUFFER [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]	CO <sub>2</sub> sequestration [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]
1	Comune di Lusiana	-5.26	-4.63
2	Comune di Valstagna	-2.03	-1.78
3	Comune di Caltrano	-5.59	-4.92
4	Comune di Roana	-5.64	-4.96
5	Comune di Asiago	-7.32	-6.44
6	Comune di Conco	-6.72	-5.91
7	Comune di Gallio	-7.56	-6.65
8	Comune di Cisman	-6.06	-5.33
9	Demanio di Rotzo	-7.60	-6.69
10	Comune di Enego	-7.16	-6.30
11	Comune di Foza	-5.09	-4.48
<b>Average</b>		<b>-6.00</b>	<b>-5.28</b>

**Table 6.6** Results of forest carbon sequestration evaluation for some municipalities in Belluno Province in Veneto Region.

Num	Name	CO <sub>2</sub> sequestration NO BUFFER [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]	CO <sub>2</sub> sequestration [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]
1	Regola di Santo Stefano	-2.38	-1.81
2	Regole di San Vito di Cadore	-3.02	-2.29
3	Magnifica regola grande dei Monti di Vodo	-4.30	-3.27
4	Regola staccata di vodo di Cadore	-0.66	-0.50
5	Domegge	-4.68	-3.56
6	Lorenzago	-5.98	-4.54
7	Regola di San Pietro	-4.23	-3.21
8	Comune di Mel	-10.00	-7.60
<i>Average</i>		<i>-4.41</i>	<i>-3.35</i>

**Table 6.7** Results of forest carbon sequestration evaluation for some municipalities in Autonomous Province of Trento.

Num	Name	CO <sub>2</sub> sequestration NO BUFFER [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]	CO <sub>2</sub> sequestration [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]
1	Comune di Folgaria	-3.77	-3.31
2	Comune di Lavarone	-3.37	-2.96
<i>Average</i>		<i>-3.57</i>	<i>-3.14</i>

**Table 6.8** Results of forest carbon sequestration evaluation in Val Varaita in Piemonte Region.

Num	Name	CO <sub>2</sub> sequestration NO BUFFER [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]	CO <sub>2</sub> sequestration [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]
1	Val Varaita	-2.28	-1.79
<i>Average</i>		<i>-2.28</i>	<i>-1.79</i>

### 5.2.2 US Pacific Northwest

In US it is common practice to invest in intensive forest management activities such as fertilization and precommercial thinning to enhance the production of the primary forest product.

Management intensity ranges from little intervention on low site productivity lands to higher management intensities involving combinations of fertilization and thinning in higher productivity lands.

In the case that an intensive forest management is adopted data are needed about the consumption of fertilizer used in seedling growth, the electrical energy required to operate forest nursery pumps and to power the growing operations and stand reestablishment activities including site preparation activities such as slash disposal and subsequent hand planting of seedlings by planting crews.

In the present study a low intensity forest management has been considered. All the activities related to the fertilization process have been excluded.

Two scenarios have been taken into account:

- State and Private Dry Forests
- State and Private Moist and Cold Forests
- National Forests Dry-Moist-Cold Forests

These scenarios differ for the rate of growing stock level, which is the highest for State and Private Moist and Cold Forest and the lowest for State and Private Dry Forests. National Forests are characterized by a closer-to-nature forest management in the last decades which has lead either to an increase in biomass stock levels and to a decrease in his rate of growing. Furthermore the three scenario are characterized by three different ratio of harvesting towards growth which are respectively 80.27%, 69.51% and 15.63%.

Although different rotation periods characterize the three scenarios, the same time frame of 75 years has been considered for the comparison.

The composition of forests has been assumed to be 50% pines (e.g. Ponderosa pine and Lodgepole) and 50% other conifer (e.g. Douglas fir, Hemlock, Cedar, Pinyon, Juniper, Spruce, Fir)

To estimate carbon stock change in biomass data collected by the Consortium on Research of Renewable Industrial Materials (CORRIM) have been used. In the first two phases of research analysis have been developed for the harvest of timber for structural wood products and paper and for the recovery of the residuals of forest harvesting operations for the Inland West.

The system has been considered a temperate mountain system with the following growing stock level:

- State and Private Dry Forests: 41 - 100 m<sup>3</sup>
- State and Private Moist and Cold Forests: 100 – 200 m<sup>3</sup>
- National Forests Dry-Moist-Cold Forests: > 200 m<sup>3</sup>

The effect of litter, dead wood and soil carbon on carbon stocks has not been considered since it goes beyond the aim of this work.

The harvest unit size, the rotation age, the average growth and the harvest/growth ratio for the three scenarios are summarized in Table 7.9.



**Table 6.9** Summary of some data collected for the Western Montana Corridor, US.

		State & Private Dry	State & Private Moist-Cold	USFS Dry-Moist- Cold
Harvest Unit Size	ha	81	81	61
Rotation Age	yr	76	66	87
Average Growth	m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup>	3.55	5.69	4.57
Harvest/Growth	%	81.34%	61.17%	18.13%

## Results

Preliminary results of carbon sequestration for the three scenarios are shown in Table 6.10.

**Table 6.10** Results of forest carbon sequestration evaluation in Western Montana Corridor, US.

	State & Private Dry	State & Private Moist-Cold	USFS Dry-Moist-Cold
Harvest Unit Size [ha]	81	81	61
Rotation Age [tr]	76	66	87
Average Growth [m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> ]	3.55	5.69	4.57
Harvest/Growth [%]	80.27%	69.51%	15.63%
CO <sub>2</sub> sequestration [MgCO <sub>2e</sub> ]	-6,453	-17,837	-21,883
CO <sub>2</sub> sequestration [MgCO <sub>2e</sub> ha <sup>-1</sup> yr <sup>-1</sup> ]	-1.05	-3.34	-4.14

The carbon sequestration per hectare per year in State and Private Moist and Cold Forests is 1.5 times the carbon sequestration in State and Private Dry Forests while the carbon sequestration in National Forests Dry-Moist-Cold Forests is almost 18 times the carbon sequestration in State and Private Dry Forests.

This is due to two factors:

- The growing stock level in National Forests Dry-Moist-Cold Forests (> 200 m<sup>3</sup>) is almost three times the growing stock level in State and Private Dry Forests (41 - 100 m<sup>3</sup>) and two times the growing stock level in State and Private Moist and Cold Forests (100 – 200 m<sup>3</sup>);
- The Harvest/Growth ratio in National Forests Dry-Moist-Cold Forests (15.63%) is 0.20 times the Harvest/Growth ratio in State and Private Dry Forests (41 - 100 m<sup>3</sup>) and 0.23 times the Harvest/Growth ratio in State and Private Moist and Cold Forests (100 – 200 m<sup>3</sup>).

The results from the two different scenarios are compared in the following table.

**Table 6.11** Comparison of results of forest carbon sequestration evaluation between Italian Alps and Western Montana Corridor, US.

	Vicenza Province	Belluno Province	Autonomous Province of Trento	Piemonte Region	State & Private Dry	State & Private Moist-Cold	USFS Dry-Moist-Cold
<b>Area [ha]</b>	15199	5147	2734	877	81	81	61
<b>Volume in forest [m<sup>3</sup> ha<sup>-1</sup>]</b>	259	311	333	293	41-100	100-200	>200
<b>Biomass Growth [m<sup>3</sup> yr<sup>-1</sup>]</b>	93478	30131	18718	4344	288	461	279
<b>Biomass Growth [m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>]</b>	6.23	6.15	6.88	5.45	3.55	5.69	4.57
<b>Harvest/Growth</b>	23.36%	47.95%	58.23%	70.20%	80.27%	69.51%	15.63%
<b>Harvested volume [m<sup>3</sup> yr<sup>-1</sup>]</b>	17986	12066	10900	3049	231	320	44
<b>CO<sub>2</sub> sequestration [MgCO<sub>2</sub>e ha<sup>-1</sup> yr<sup>-1</sup>]</b>	-6.00	-4.41	-3.57	-2.28	-1.05	-3.34	-4.14

The comparison of the two areas of study show higher values of standing volume in Italian Alps forests than Pacific Northwest forests in all the case studies considered. This leads to higher biomass growth since it depends on the initial biomass present in forest.

With the exception of USFS Dry-Moist-Cold Forests which register the lowest value of Harvest/Growth ratio, the Italian scenario presents lower values of Harvest/Growth ratio for all the case studies.

Despite the USFS Dry-Moisture-Cold Forests having the lowest value of Harvest/Growth and a high value of volume in forest, its biomass growth is very low. Italian forests with comparable levels of volume in forest and higher ratio of harvesting have biomass growth from 19% up to 51% higher than USFS Dry-Moist-Cold.

This may be caused by the age of species: older trees absorb carbon at lower rates influencing the overall biomass growth. A forest management with very low values of Harvest/Growth ratio can sometimes not be the best option to maximize the forest carbon absorption.

The carbon sequestration between the two scenarios is compared. In average forests in Veneto Region sequester from 35% up to four times more carbon than respectively USFS Dry-Moist-Cold Forests and State & Private Dry Forests.

## Chapter 7

### **Numerical approach to include time dependent natural phenomena dynamics, delayed emissions and carbon storage into the LCA**

In this section a new approach will be presented to include time dependent carbon sequestration, forest dynamics, delayed emissions and carbon storage into the Life Cycle Assessment of wood products.

#### **7.1 Introduction**

In Life Cycle Assessment the potential environmental impacts are evaluated for the selected impact categories by expressing the emissions of each pollutant in terms of a reference substance. For this purpose the emission values are multiplied by some factors called characterization factors. The total impact is expressed in terms of emissions of the "equivalent" reference substance which means that an equivalent amount of the reference substance is used to express the total impact of the different pollutants.

For global warming, the characterization factors are simpler measures or metrics that are based on results from complex models and that are used to quantify the contributions to climate change of emissions of different substances thus acting as 'exchange rates' (IPCC, 2013).

Metrics can be given in absolute terms (e.g.,  $\text{K kg}^{-1}$ ) or in relative terms by normalizing to a reference gas — usually  $\text{CO}_2$ . To transform the effects of different emissions to a common scale — often called 'CO<sub>2</sub> equivalent emissions'—the emission ( $E_i$ ) of component  $i$  can be multiplied with the adopted normalized metric ( $M_i$ ):  $M_i \times E_i = \text{CO}_2\text{-eq}_i$  (IPCC, 2013).

One of the fundamental limitations of this approach is that the characterization factors are constant values. In LCA it is assumed that all emissions are released at time zero and the potential impacts are assessed for the horizon time chosen. Consequently the LCA is a static approach and it can be considered as a picture of the environmental impacts at a given time.

Unlike other product categories, however, timing is of crucial importance in the life cycle of forest products. The life cycle of wood products, in fact, starts with the forest, where several phenomena simultaneously occur following different dynamics. Carbon dioxide is removed from the atmosphere through the photosynthesis activity and transformed in biomass for trees growth. After harvesting, wood residues left in forest progressively release to the atmosphere the carbon content of their biomass, as  $\text{CO}_2$  or  $\text{CH}_4$  depending on the conditions, while part of it goes to restore the carbon in soil. Furthermore fires contribute to the sudden release of variable quantities of  $\text{CO}_2$  based on their magnitude.

In order to replace the harvested biomass, the forest can take decades and forest management

rotation periods are therefore typically of the order of magnitude of 40-100 years.

Furthermore, different wood products have different life span. If wood is used for bio-energy the production of the raw material can take several years for the growth of biomass but the life span of the product is normally considered within one year. On the contrary, when wood is used as a material for buildings, its life time can be of several decades.

Because these dynamics have timing comparable with the time horizon of the LCA study, the temporal aspect is crucial in the life cycle of wood products. Different situations can be summarized in the following categories:

1. Natural phenomena dynamics: carbon sequestration, decomposition of residues left in forest, soil carbon, fires;
2. Carbon storage and delayed emissions: carbon temporarily sequestered from the atmosphere and stored in wood products e.g. long lasting wood products after their life span (e.g. 70 years) can be either disposed in landfill (slow release of emissions over time) or in incinerator (single emission delayed in time);

In this chapter an approach is presented to simultaneously cope with all these issues.

## 7.2 Methodological review

### 7.2.1 The Radiative Forcing concept

In LCA the impact on global warming is evaluated through some characterization factors called Global Warming Potentials (GWP). The Global Warming Potential (GWP) index is based on the time-integrated global mean RF of a pulse of emission of 1 kg of some compound (i) relative to that of 1 kg of the reference gas CO<sub>2</sub>. The GWP of component i is defined by (IPCC, 2013):

$$GWP_i = \frac{\int_0^{TH} RF_i(t) dt}{\int_0^{TH} RF_r(t) dt} = \frac{\int_0^{TH} RE_i \cdot C_i(t) dt}{\int_0^{TH} RE_r \cdot C_r(t) dt} = \frac{AGWP_i}{AGWP_r}$$

GWP<sub>i</sub> = Global Warming Potential of GHG

TH = time horizon

RF<sub>i</sub> = Radiative Forcing of GHG i

RF<sub>r</sub> = Radiative Forcing of the reference GHG (CO<sub>2</sub>).

RE<sub>i</sub> = RF per unit mass increase in atmospheric abundance of component i (Radiative Efficiency)

C<sub>i</sub>(t) = time-dependent abundance of i and the corresponding quantities for the reference gas (r) in the denominator.

GWPs are function of the Radiative Forcing (RF), which is defined as the change in net (down minus up) irradiance at the tropopause after allowing for stratospheric temperatures to readjust to

radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values (IPCC, 2007).

The RF is a concept used for quantitative comparisons of the strength of different human and natural agents in causing climate change. Differences in RF are the cause of the increase of the mean global temperature on the terrestrial surface. Positive RFs lead to a global mean surface warming and negative RFs to a global mean surface cooling.

The RF depends on the relative abundance of that GHG in the atmosphere and on its Radiative Efficiency (RE). The relative abundance of the GHG in the atmosphere is measured through some functions called decay functions which tell how long a GHG stays in the atmosphere once it has been released. They depend on the GHG residence time in the atmosphere and its bulk concentration. GWPs include both these factors by means of a function which expresses the decay of a unit-pulse of GHG to the atmosphere (decay function) due to the effect of the environment.

The decay of a pulse of GHG (CO<sub>2</sub> excluded) follows a first order decay equation in function of the lifetime in the atmosphere (IPCC, 2013):

$$C(t) = e^{-\frac{t}{\tau}}$$

$\tau$  = lifetime. The values of the GHGs lifetimes changed between the 4<sup>th</sup> Report IPCC (IPCC, 2007) and the 5<sup>th</sup> IPCC Report (IPCC, 2013) and are reported in Table 7.1:

Table 7.1 GHGs lifetimes according to the 4<sup>th</sup> and 5<sup>th</sup> IPCC Report.

IPCC Report	$\tau_{\text{CH}_4}$ (years)	$\tau_{\text{N}_2\text{O}}$ (years)
IPCC 2007	12	114
IPCC 2013	12.4	121

The decay of a pulse of CO<sub>2</sub> with the time t is based on the revised version of the Bern Carbon cycle model and is given by (IPCC, 2013):

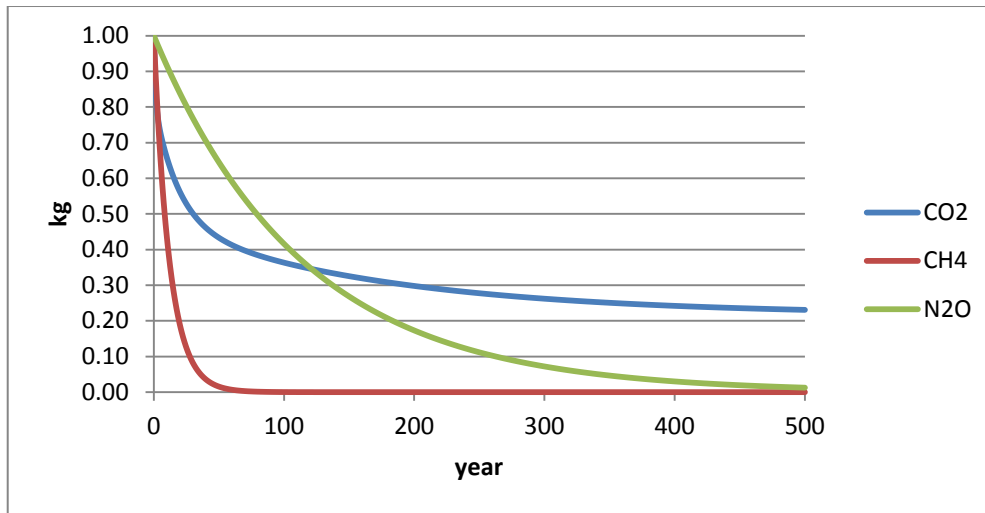
$$a_0 + \sum_{i=1}^3 a_i e^{-t/\tau_i}$$

The values of the parameters changed between the 4<sup>th</sup> IPCC Report (IPCC, 2007) and the 5<sup>th</sup> IPCC Report (IPCC, 2013) and are reported in **Errore. L'origine riferimento non è stata trovata.**

Table 7.2 Parameters values for the decay function of a pulse of CO<sub>2</sub> according to the 4<sup>th</sup> and 5<sup>th</sup> IPCC Report.

IPCC Report	$a_0$	$a_1$	$a_2$	$a_3$	$\tau_1$ (years)	$\tau_2$ (years)	$\tau_3$ (years)
IPCC 2007	0.217	0.259	0.338	0.186	172.9	18.51	1.186
IPCC 2013	0.2173	0.2240	0.2824	0.2763	394.4	36.54	4.304

The decays of a unit-pulse of different GHGs are shown in Figure



**Figure 7.1** Decay of 1 kg pulse of GHGs.

The Radiative Efficiency (RE) is the RF per unit mass increase in atmospheric abundance of component  $i$  and is calculated for a perturbation of 1 unit ( $C$ ) to the background concentration ( $C_0$ ) by the following equations (Table 8.SM.1, Chapter 8, Supplementary Material, 5<sup>th</sup> IPCC Report (IPCC, 2013)):

$$\Delta F = \alpha \ln \frac{C}{C_0}$$

where  $C = \text{CO}_2$  in ppm,  $\alpha = 5.35$

$$\Delta F = \alpha(\sqrt{M} - \sqrt{M_0}) - (f(M, N_0) - f(M_0, N_0))$$

where  $M = \text{CH}_4$  in ppb,  $\alpha = 0.036$

$$\Delta F = \alpha(\sqrt{N} - \sqrt{N_0}) - (f(M_0, N) - f(M_0, N_0))$$

where  $N = \text{N}_2\text{O}$  in ppb,  $\alpha = 0.12$

where

$$f(M, N) = 0.47 \ln[1 + 2.01 \cdot 10^{-5}(MN)^{0.75} + 5.31 \cdot 10^{-15}M(MN)^{1.52}]$$

The same equations are used to evaluate the change in RF for the increase of GHG concentration in

the atmosphere between the present day (approximately 2005 in the 4<sup>th</sup> IPCC Report and 2011 in the 5<sup>th</sup> IPCC Report) and the beginning of the industrial era (approximately 1750).

The background concentrations ( $C_0$ ), the radiative efficiency (RE) and the radiative forcing (RF) reported in the 4<sup>th</sup> (IPCC, 2007) and in the 5<sup>th</sup> IPCC Report (IPCC, 2013) are listed in **Errore. 'origine riferimento non è stata trovata.**<sup>3</sup> for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O.

**Table 7.3** Background concentrations ( $C_0$ ), radiative efficiency (RE) and radiative forcing (RF) of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O reported in the 4<sup>th</sup> and in the 5<sup>th</sup> IPCC Reports.

IPCC Report	IPCC 2013			IPCC 2007		
	$C_0$	RE (W m <sup>-2</sup> ppb <sup>-1</sup> )	RF (W m <sup>-2</sup> )	$C_0$	RE (W m <sup>-2</sup> ppb <sup>-1</sup> )	RF (W m <sup>-2</sup> )
CO <sub>2</sub> (ppm)	391	1.37e <sup>-5</sup>	1.82	379	1.4e <sup>-5</sup>	1.66
CH <sub>4</sub> (ppb)	1803	3.63e <sup>-4</sup>	0.48	1774	3.7e <sup>-4</sup>	0.47
N <sub>2</sub> O (ppb)	324	3.00e <sup>-3</sup>	0.17	319	3.03e <sup>-3</sup>	0.16

The impact of each GHG is given by the integral of the radiative forcing over time. Conventionally the GWP are assessed by the IPCC for 25, 100 and 500 years.

In traditional LCA GWPs are assigned to the GHG emissions for the horizon time chosen (normally 100 years as recommended by the guidelines).

The 5<sup>th</sup> IPCC Report provides the equations for the Absolute Global Warming Potentials for carbon dioxide and other greenhouse gases:

$$AGWP_{CO_2}(T_H) = \int_0^{T_H} RE_{CO_2} \cdot C_{CO_2}(t) dt = RE_{CO_2} \left[ a_0 T_H + \sum_{i=1}^N a_i \tau_i \left( 1 - e^{-\frac{T_H}{\tau_i}} \right) \right]$$

$$a_0 = 0.2173; a_1 = 0.2240; a_2 = 0.2824; a_3 = 0.2763$$

$$\tau_1 = 394.4; \tau_2 = 36.54; \tau_3 = 4.304$$

$$AGWP_{GHG}(T_H) = \int_0^{T_H} RE_{GHG} \cdot C_{GHG}(t) dt = RE_{GHG} \tau_{GHG} \left( 1 - e^{-\frac{T_H}{\tau_{GHG}}} \right)$$

These equations, however, are integrated for a pulse emission. They do not include the emissions as function of time. Since the impact on global warming is evaluated through the radiative forcing, which is a function of time, natural phenomena, delayed emissions and carbon storage can have a different effect on global warming because the temporal dynamics and the time when the emissions are released are crucial aspects to be considered.

### ***7.2.2 Natural phenomena dynamics***

In LCA natural phenomena occurring in the forest are generally not considered in the evaluation. Based on the carbon neutrality assumption, as described in Chapter 1, emissions of CO<sub>2</sub> from the combustion of biomass for energy in national inventories are currently assumed to have no net RF (IPCC, 2013).

This is based on the assumption that these emissions are compensated by biomass regrowth (carbon neutrality assumption) (IPCC, 2013). The carbon neutrality assumption states that the carbon dioxide emitted to the atmosphere by combustion equals the amount of carbon dioxide previously absorbed by the forest to produce the biomass.

Under the Kyoto Protocol bioenergy is considered “carbon neutral”. The carbon stock changes that accompany the production of biomass is accounted in the “Land Use, Land Use Change and Forestry” sector and they are not counted unless the country has elected to include the Forest Management in their Kyoto Protocol account (Brandão et al., 2013).

The carbon neutrality assumption is included in LCA standards, EPA Guidelines, IPCC 2014, IPCC Guidelines, PAS 2050:2011, ILCD (BSI, 2011; EPA, 2011; European Commission, 2010; IPCC, 2013, 2006).

In conventional LCA carbon neutrality is often assumed for biologically based products and biogenic carbon fluxes are consequently omitted regardless of the difference in timing of uptake and release. Conventional LCA methodology does not consider the timing of emissions and removals but uses a constant characterization factor throughout the life cycle of the product, process or service.

To calculate net GHG emissions from biologically based products the amount of CO<sub>2</sub> absorbed during the biomass growth in the first stage of the product life cycle is typically subtracted from the amount of CO<sub>2</sub> (including biogenic) released to the atmosphere during all life cycle stages of the product (Brandão et al., 2013).

ILCD and EPA guidelines and the PAS 2050 recommend to treat biogenic emissions apart from fossil emissions according to the carbon neutrality assumption, simplifying the problem of quantifying the absorption of carbon in the forest and its dynamics.

### ***7.2.3 Carbon storage and delayed emissions***

Methodologies to calculate the effect of carbon storage and delayed emissions have been lately object of study and discussed at international level.

The main methods are the Moura-Costa and the method Lashof accounting. The Moura-Costa method and the Lashof accounting were discussed for GHG inventory for the Kyoto Protocol as alternative to the annual stock change method of the IPCC Good Practice Guidance for LULUCF.



They have been lately proposed for LCA-related applications. Based on those methods the PAS 2050:2008 proposed a simplified methodology to quantify the carbon storage that discount from the total emissions of the effect the storage of carbon for the life of the product through a coefficient discount. The ISO 14067, the GHG Protocol and the revised PAS 2050:2011 does not require that any credits is given to temporary storage in the base calculation. Nevertheless these standards allow a supplementary figure to be calculated that does include temporal aspects to be reported separately.

### 7.2.3.1 The Moura-Costa method

This method evaluates the carbon storage by evaluating the number of years the CO<sub>2</sub> is removed and kept out of the atmosphere, converting it in terms of impact on global warming and subtract it from the GHG inventory.

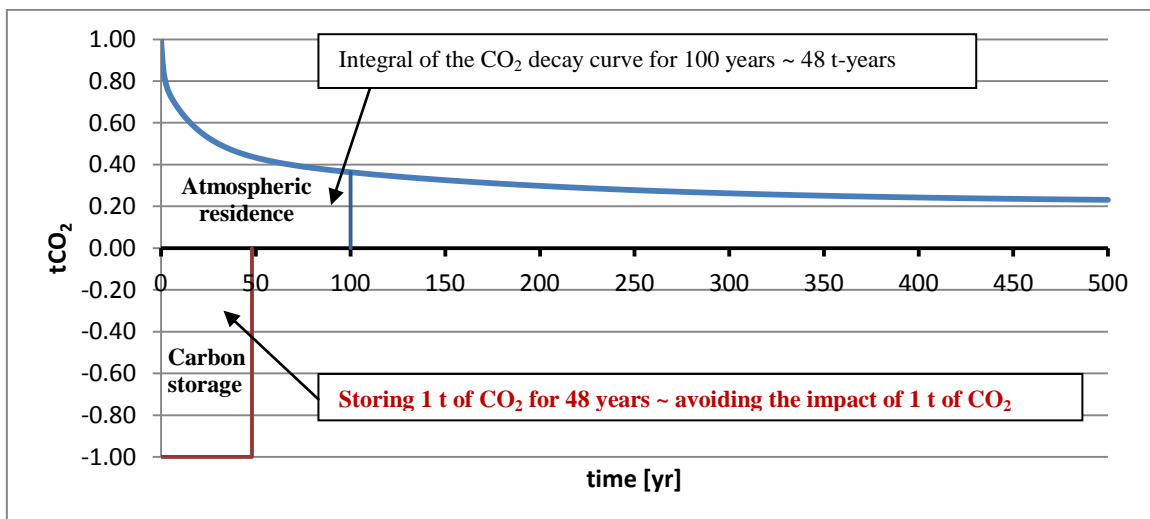


Figure 7.2 Representation of the Moura-Costa method.

The impact on global warming is evaluated through the cumulative radiative forcing integrated over a given time horizon caused by a one-tonne pulse-emission of CO<sub>2</sub>.

The integral of the CO<sub>2</sub> decay curve for a time horizon of 100 years is approximately 48 tonne-years. According to this calculation, storing one ton of CO<sub>2</sub> for 48 years is equivalent to avoiding the impact of 1 tonne of CO<sub>2</sub>, which also means that storing one tonne of CO<sub>2</sub> for one year can compensate the impact of an emission of 0.02 tonne (1/48) of CO<sub>2</sub> (Brandão et al., 2013; Levasseur et al., 2010).

In this way the Moura-Costa method evaluates an equivalence factor for crediting sequestration and storage of CO<sub>2</sub> for the number of years it is removed and kept out of the atmosphere. Since this credit is assumed to compensate for the impact of an equivalent GHG emission, it can then be

subtracted from a GHG inventory.

One issue with this option is that it adopts a fixed duration over which impacts occur after an emission regardless of when the emission is released. This means that the benefit of sequestering a unit mass of carbon for a number of years equal to the time horizon and then releasing it is higher than the total impact of the emission of a similar amount integrated over this time horizon (Brandão et al., 2013).

### 7.2.3.2 The Lashof accounting

Likewise the Moura-Costa method, the Lashof accounting aims to calculate an equivalence factor for crediting carbon storage for the number of years it is removed from the atmosphere.

According to the Lashof accounting, storing carbon for a given number of years is equivalent to delaying a CO<sub>2</sub> emission until the end of the storage period.

The decay curve is then pushed back from a certain number of years, equal to the storage time, and the portion of the initial 48 tonne-years area which is now beyond the 100-year time horizon corresponds to the benefits of the perceived storage. For example, when storing one tonne of CO<sub>2</sub> for a period of 48 years, the portion of the area under the decay curve beyond 100 years is 19 tonne-years. This means that storage for 48 years would be equivalent to avoiding an emission of 0.4 tonne (19/48) of CO<sub>2</sub>; i.e. 40% of the value of 1 tonne proposed using the Moura-Costa method for the same sequestration and storage period (Brandão et al., 2013; Levasseur et al., 2010).

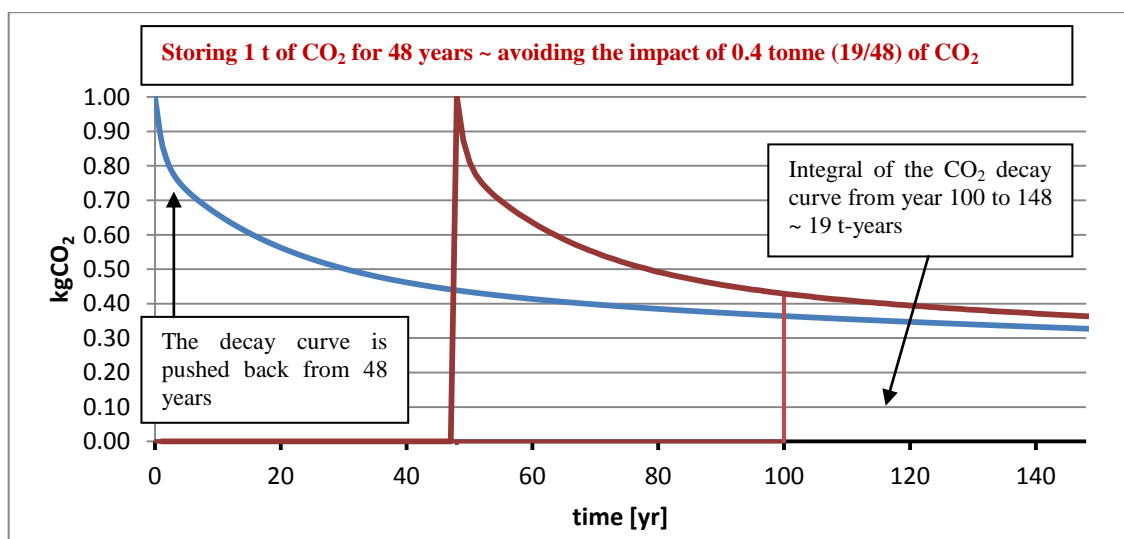


Figure 7.3 Representation of the Lashof accounting method.

Contrary to the Moura-Costa approach the application of this method never results in more than 100% credit when delaying an emission. An emission would have to be delayed by 100 years in

order to be considered neutral.

Despite the same characterization factors being derived from both this and the Lashof methods one important difference between the two is that the dynamic LCA approach fixes the beginning of the accounting period and the Lashof approach does not. This implies that removing a certain amount of atmospheric carbon always has the same climate impact in the latter method but not in the former.

### 7.2.3.3 The PAS 2050

Based on the Lashof accounting, a simplified methodology for the evaluation of the carbon storage and delayed emissions was developed and included in the PAS 2050:2008 (BSI, 2008).

The impact of carbon storage associated with the product is expressed as CO<sub>2</sub>e and deducted from the total. A dual approach is adopted:

- for short storage times, a linear approximation of the Lashof accounting;
- for long storage times, the average amount of carbon stored over 100 years.

#### 1- Short carbon storage times

When the full carbon storage benefit of a product exists for between 2 and 25 years after the formation of the product (and no carbon storage benefit exists after that time) the weighting factor to be applied to the CO<sub>2</sub> storage benefit over the 100-year assessment period is calculated according to:

$$\textit{Weighting factor} = \frac{(0.76 \cdot t_0)}{100}$$

where

$t_0$  = the number of years the full carbon storage benefit of a product exists following the formation of the product

#### 2-Long carbon storage times

In cases not covered in 1- the weighting factor to be applied to the CO<sub>2</sub> storage benefit over the 100-year assessment period is calculated according to:

$$\textit{Weighting factor} = \frac{\sum_{i=1}^{100} x_i}{100}$$

where

$i$  = each year in which storage occurs

$x$  = the proportion of the total storage remaining in any year  $i$

Similarly the PAS 2050 distinguishes two cases of delayed emissions:

1- Single release

Where emissions from the use phase or the final disposal phase of a product occur as a single release within 25 years of the formation of the product, the weighting factor to be applied to the GHG emissions released at that time is calculated according to:

$$\textit{Weighting factor} = \frac{100 - (0.76 \cdot t_0)}{100}$$

where

$t_0$  = number of years between formation of the product and the single release of the emissions.

2- General case: delayed release

In cases not covered in the point 1) the weighting factor to be applied to the GHG emissions in the atmosphere is calculated according to:

$$\textit{Weighting factor} = \frac{\sum_{i=1}^{100} x_i(100 - i)}{100}$$

where

$i$  = each year in which emissions occur

$x$  = proportion of total emissions occurring in any year  $i$

### 7.3 Methodology developed to include temporal aspects into the LCA

In this paragraph a methodology will be presented to cope with the issues described above: the carbon neutrality assumption and carbon storage. As for Moura-Costa, Lashof accounting and PAS 2050:2008 methods, the methodology involves considering the temporal aspect in Radiative Forcing to assess the impact on global warming.

The formulas proposed by the IPCC are valid in case emissions are released instantly. In fact in the Supplementary material the Radiative Forcing functions are integrated without considering the temporal trend of the emissions. If the emission (or absorption) was not a point emission but had a certain trend over time, and the equation was available, it would be possible to analytically evaluate the integral of the product between the emissions and the radiative forcing. For simplicity, here integrals will be approximated with the summation. For this reason the proposed method can be easily applied to a lot of different contexts and situations where timing is important.

### 7.3.1 Materials and methods

#### Step 1. Selection of the horizon time and subdivision in intervals of unit length

Chose a horizon time for the evaluation,  $H_T$  (e.g. 20, 100 or 500 years according to IPCC) and split it in intervals of unit length,  $t$ , e.g. from 1 to 100.

#### Step 2. Evaluation of carbon sinks and emissions

Evaluate all carbon sinks and emissions (natural and anthropogenic) that are part of the life cycle and express them in terms of kgGHG, e.g. CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O.

#### LCI results

Extract the Life Cycle Inventory (LCI) of the product system, i.e. the LCA results before characterization. This includes all the emissions associated with the life cycle of the system product, from forest operations of harvesting, hauling, off-road and on-road transportation, distribution, until the end of life. Combustion emissions can also be included in the LCI.

The LCI should include both natural and anthropogenic emissions, in particular it should include the biogenic carbon dioxide and it can be referred to either the all life cycle or subdivided for unit process referring the emissions to the functional unit.

The LCI will be considered as point emissions occurring at the beginning of the horizon time. If there are delayed emissions, e.g. emissions from landfill, these should be treated separately.

#### Carbon sequestration

Carbon sequestration can be evaluated by:

- IPCC stock change method like applied in Chapter 6 of this dissertation. Since this method does not provide information about the rate of growth, if that information cannot be found from other sources, it has to be assumed that the absorption of carbon is constant throughout the rotation period.
- Forest Vegetation Simulator: it returns values of carbon stock at different times, evaluating them from empirical data for the time step and the rotation period chosen as parameters.
- Mathematical model: it can be applied over the horizon time of the study to mathematically predict carbon stocks.

If carbon stocks values over time have been calculated, carbon sinks can be approximated with the carbon stocks difference between two successive time step:

$$C_{sink}(t) = \frac{dC_{stock}(t)}{dt}$$

$$C_{sink}(t + 1) \approx \frac{C_{stock}(t + 1) - C_{stock}(t)}{\Delta t}$$

C sink = carbon sink

C stock = carbon stock, assumed to be around 50% of the total woody biomass.

The carbon sequestration is related to the carbon sink via the carbon and carbon dioxide molecular weights:

$$C_{seq}(t) = C_{sink}(t) \cdot \frac{MW_{CO_2}}{MW_C}$$

Cseq = carbon sequestered

MWCO<sub>2</sub> = Molecular weight of CO<sub>2</sub>

MWC = Molecular weight of carbon (IPCC, 2006)

#### Wood decomposition

Wood decomposition, either in forest or in landfill, can be estimated through decay equations, i.e. the one used in Chapter 8 of this dissertation (IEA, 2006) if a LCI is not available.

#### Other natural phenomena dynamics

All the natural phenomena for which data or models are available related to the carbon cycle, e.g. fires, soil carbon, stump and roots decay, can be included in this analysis.

### **Step 3. Allocation and normalization of sinks and emissions to the functional unit**

#### *Allocation*

If sinks and emissions were not already allocated as result of the calculation described in step 2, allocation should be performed on mass value based on the product system biomass ratio to the total biomass involved in the process. In the LCI the allocation should be included in the simulation model and the emissions should be already referring to the functional unit.

If the FVS was used for carbon sequestration, the software returns values of carbon stock for standing and harvested carbon for different tree components: stem, top, foliage, branches, bark, stump and roots. Depending on the product system of the study, only the fraction of biomass object of study should be selected.

#### *Normalization*

Scale all carbon stocks to the amount of carbon needed per functional unit, e.g. 1.7 BDmT of biomass is needed to produce 1 BDmT of residues (0.7 BDmT of biomass is left in forest to decompose).

#### Step 4. Evaluation of the dynamic GHG emissions profiles of the product system

All the emission and sequestration sources should be allocated, normalized and assigned to the time when they are released or absorbed and for the number of years they are released/absorbed for each GHG.

If there are delayed emissions, those should be placed at the time when they occur, e.g. after 50 years from the beginning of the horizon time and for the number of years they occur.

If carbon sinks were evaluated by the IPCC stock change method like in Chapter 6 of this dissertation, not having information about the rate of growth, it can be assumed that the absorption of carbon is constant throughout the rotation period, so the total carbon sequestration value should be divided by the number of years of the rotation period.

If the Forest Vegetation Simulator was used, values of biomass growth will be available for each time step, calculated from empirical data.

For each GHG, sum the emissions and sequestrations (which will have negative sign) values for each time  $t$  of the horizon time, obtaining the dynamic GHG emissions profile of the product system, which it will be referred to as  $Y_{GHG}(t)$ . The number of emission profiles equal the number of emitted GHGs.

$$Y_j(t) = \sum_{j=1}^N y_j(t)$$

#### Step 5. Radiative Forcing evaluation to the dynamic GHG emissions profiles

Apply the decay functions to the GHG emission profiles  $y_{GHG}(t)$  expressed in kgGHG for each value of  $t$  of the horizon time and for each value of  $y_{GHG}$ :

$$[C_{GHG}(t)] = C_{GHG}(t) \cdot y_{GHG}(t)$$

The decay function for a 1 kg pulse emission of CO<sub>2</sub> and other GHG is evaluated through :

$$C_{CO_2}(t) = a_0 + \sum_{i=1}^3 a_i e^{-\frac{t}{\tau_{CO_2}}}$$

$$C_{GHG}(t) = e^{-\frac{t}{\tau_{GHG}}}$$

The lifetimes of different GHGs are listed in Table 8.A.1.

Evaluate the Radiative Efficiency expressed in terms of  $W m^{-2} kg^{-1}$ . To convert the RE values given per ppbv values to per kg (Shine et al., 2005) they must be multiplied by  $(MA/Mi)(109/TM)$  where MA is the mean molecular weight of air (28.97 kmol<sup>-1</sup>), Mi is the molecular weight of species i

and  $T_M$  is the total mass of the atmosphere,  $5.1352 \times 10^{18}$  kg (Trenberth and Smith, 2005).

The RE values per ppb are reported in Table 8.A.1 of the Chapter 8 of the IPCC 5th Report.

Evaluate the Radiative Forcing by multiplying the decay function by the Radiative Efficiency for each time  $t$ .

$$RF_{GHG}(t) = RE_{GHG} \cdot [C_{GHG}(t)]$$

Emissions will have a positive RF while sequestered carbon dioxide will have a negative RF.

Evaluate the Cumulative Radiative Forcing summing up the contributions of each  $C_{GHG}$

$$RF_{cum} = \sum_{i=1}^{T_H} RF_{i,GHG}(t)$$

### Step 6. AGWP<sub>LCA</sub> evaluation

Evaluate the Absolute Global Potential of the LCA is the Cumulative Radiative Forcing over the horizon time.

$$AGWP = \int_0^{T_H} RF_{GHG} dt = \int_0^{T_H} RE_{GHG} \cdot [C_{GHG}(t)] dt \approx \sum_{i=0}^{T_H} RE_{GHG} \cdot [C_{GHG}(t)]$$

The integral can be approximated with a summation.

### Step 6. GWP evaluation

The decay function has been applied to the greenhouse gas emissions (carbon dioxide and other GHG) to all the phases of the life cycle assessment.

The temporal aspect has been evaluated considering the cumulative value of emissions over time which influence the radiative forcing.

Each GHGs mass flow is multiplied by its GWP to obtain the corresponding GHG emission which is expressed in terms of CO<sub>2e</sub>. In the conventional approach GWPs are constant characterization factor to relate the impact of each GHG to an equivalent impact of CO<sub>2</sub>. Thus it is possible to evaluate a GWP as the ratio between the dynamic to the static AGWPs:

$$GWP = \frac{AGWP_{CO_2}^{dyn}}{AGWP_{CO_2}^{stat}}$$



## **7.4 Conclusions**

In this chapter a methodology was developed which, through the radiative forcing concept, allows to incorporate dynamic phenomena into the LCA. The method can be directly used to LCA studies to evaluate the impact on Global Warming associated to the entire life cycle. Indeed, it is particularly useful to assess the impacts of delayed emissions; carbon sequestered from the atmosphere into wood products, emissions released gradually over time and carbon sequestration. The method is simple to apply since it is based on numerical calculation. Thus, even if a mathematical model is not available to describe a dynamic process or a natural phenomenon but empirical data or equations are available, it allows to include temporal dynamics in a simple way significantly improving the accuracy of the LCA evaluation.

In the next Chapter, this method will be applied to a case study in the U.S. Pacific Northwest to include carbon sequestration, residues decomposition and biogenic emissions into the LCA.



## Chapter 8

### Development of a Dynamic Life Cycle Assessment through the Radiative Forcing methodology<sup>2</sup>

**Authors:** Pierobon F., Ganguly I., Anfodillo T., Eastin I. L.

#### 8.1 Abstract

The “carbon neutrality” assumption plays an important role in the evaluation of the global warming potential (GWP) of bioenergy relative to fossil fuels. In the case of woody bioenergy, this assumption implies that the carbon dioxide emitted during the combustion of the biomass is equal to the carbon dioxide sequestered from the atmosphere within that biomass. However, the collection and conversion of woody biomass requires energy inputs in various forms that produce emissions to the air or water.

To be able to estimate the overall environmental burdens associated with converting woody biomass to bioenergy, and the net reduction in greenhouse gas (GHG) emissions to the atmosphere by avoiding the use of fossil fuel, a life cycle assessment (LCA) is the internationally recognized method of choice. However, the carbon neutrality of woody biomass and the environmental impacts associated with wood-based bioenergy are hotly debated in national and international arenas. This study presents a comprehensive evaluation of the environmental impacts of woody biomass-based bioenergy and proposes a GWP impact assessment methodology using radiative forcing for incorporating the dynamics of carbon sequestration, decomposition of residues and biomass processing in the life cycle assessment of bioenergy.

#### 8.2 Introduction

Life cycle assessment (LCA) is a popular tool for the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product throughout its life cycle (ISO, 2006a, 2006b). The impact categories generally included in LCA studies are global warming, ozone depletion, eutrophication, acidification, smog formation, ecotoxicity, human health criteria, human health cancer and human health non-cancer.

Among these, the impact on global warming is the focal indicator for bioenergy considerations.

The impact on global warming is assessed through the evaluation of the greenhouse gas (GHG)

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emissions, expressed in terms of carbon dioxide equivalence (CO<sub>2</sub>e). In the LCA framework the GHG emissions are classified in two distinct categories, fossil and biogenic. Fossil emissions are those that are released through the combustion or decomposition of fossilized material (e.g., coal, oil and natural gas). Biogenic emissions are those that are released through combustion or decomposition of biomass (i.e., material of biological origin) (BSI, 2011).

Based on the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010) and the EPA accounting framework (EPA, 2011), the impact on global warming is entirely attributed to fossil GHG emissions while biogenic emissions are considered to be carbon neutral and are not reported in the LCA indicators.

The carbon neutrality assumption is based on the idea that the release of carbon dioxide during the conversion of biomass to energy is balanced by the carbon sequestered within that biomass.

In carbon accounting terms, carbon sequestration during biomass growth is accounted for as a negative emission. The net GHG emissions from biologically based energy products is evaluated by subtracting the amount of CO<sub>2</sub> taken up during biomass growth in the first stage of the product life cycle from the amount of CO<sub>2</sub> (including biogenic) released to the atmosphere during all life cycle stages of the product (Brandão et al., 2013). Among the new and developing approaches, the ISO 14067 (ISO, 2013a) and GHG Protocol (WRI and WBCSD, 2013), as well as the revised Publicly Available Specification (BSI, 2011), require that the biogenic contribution be excluded from the accounting although it may be calculated and reported separately.

The assumption of carbon neutrality is adopted in conventional LCA since the timing of emissions relative to removals is not considered. For this reason, the benefit to temporarily removing carbon from the atmosphere is not assigned. As observed by Brandão et al., (2013), although the net exchange may be the same, their different timing with respect to the order of uptake and release of carbon will lead to different trajectories of atmospheric CO<sub>2</sub> concentrations.

Various methods have been proposed for considering the dynamics of the carbon cycle in assessing sequestration and temporary storage of carbon and delayed GHG emissions.

The two most popular methods in the literature are the Moura-Costa method and the Lashof accounting method (Sathre and Gustavsson, 2012). These methods evaluate the impact on global warming using the radiative forcing approach and produce equivalence factors that can be used to account for carbon storage based on the number of years the carbon is sequestered.

However, these methods do not include the temporal dynamics of emissions and sequestration.

The LCA approach that considers the temporal distribution of GHG emissions over the life cycle of a product is known as “dynamic LCA”. Dynamic LCA utilizes the radiative forcing metrics to produce dynamic characterization factors. These dynamic characterization factors are then used to substitute for the characterization factors used in the traditional LCA (Brandão et al., 2013). The dynamic LCA has recently been adopted to evaluate the impact of renewable resources (Kirkinen et

al., 2008; Kendall et al., 2009; O'Hare et al., 2009; Levasseur et al., 2010; Cherubini et al., 2011a, 2011b) applied the radiative forcing approach to calculate the integrated impact of carbon uptake during biomass growth in the forest with GHG emissions during biomass burns using an analytical model. However, no auxiliary life cycle inputs for harvesting and biomass processing were considered in this study.

The objective of this study was to develop a dynamic LCA of residual woody biomass-based bioenergy by incorporating the temporal aspect of carbon sequestration. The woody feedstock in this study was residual woody biomass that was left in slash piles at the harvest landing following a commercial harvest (clearcut/commercial thinning) operation. Hence, this study incorporated the dynamic nature of carbon sequestration in the overall supply chain LCA of woody biomass-based bioenergy.

The specific objectives of this study were to:

1. perform a “cradle-to-grave” life-cycle assessment of woody biomass-based bioenergy,
2. evaluate the temporal dynamics of carbon sequestration and decomposition of residues in a particular forest type in the Pacific Northwest region, and
3. apply a radiative forcing analysis that incorporates the temporal aspect of carbon sequestration within an LCA framework.

## **8.3 Materials and Methods**

### ***8.3.1 Area of study***

The geographic area of the study can significantly influence the LCA results because of differences in forest management intensity or the type of forest. This paper focuses on the industrial forest land and forestry practices in the Pacific Northwest (PNW) region west of the Cascade mountains.

Specifically, for this study the forest inventory data (FIA, 2014) for industrial forest land in Grays Harbor County, Washington State were used. This county was selected for its abundance of commercial forest lands, which are typical of the commercial forest lands located in western Washington and Oregon. Moreover, easy access to state and national highways makes this region ideal for the production of woody biomass.

### ***8.3.2 System boundary***

The system boundary for the study, shown in Figure 8.1, comprises all of the biomass harvest, collection, and in-woods processing related activities. The system boundary for this study also included transportation of the woody biomass from the forest to a hypothetical bioenergy facility as well as the end of life use (e.g., domestic heating).

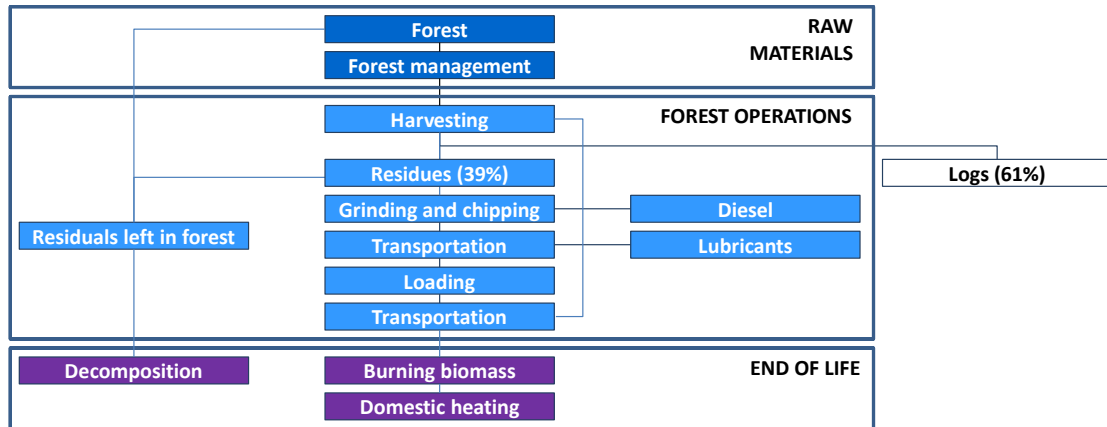


Figure 8.1 System boundaries of the LCA

The functional unit for the study was 1 bone-dry metric ton (BDmT) of woody biomass and the LCA approach is a cradle-to-grave analysis. The time frame of the evaluation was 100 years (as recommended by the ISO guidelines).

### 8.3.3 Carbon sequestration

A representation of the carbon cycle in forests is shown in Figure 8.2.

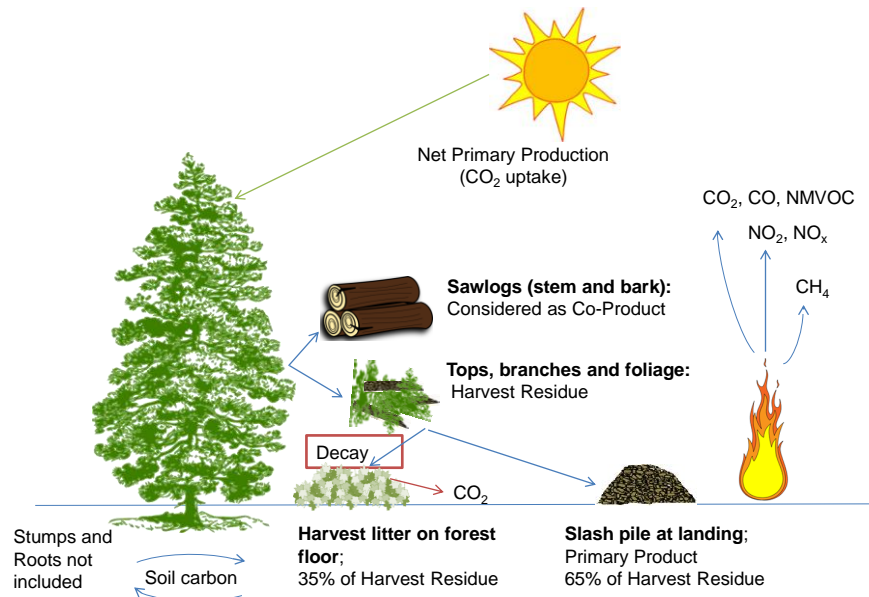


Figure 8.2. Representation of the carbon balance in forest.

Carbon dioxide is absorbed from the atmosphere by trees through photosynthesis and transformed into biomass during growth. A fraction of the carbon absorbed is then returned to the atmosphere

through respiration or from natural disturbances (e.g., fire), which not only emit CO<sub>2</sub> but also other pollutants, including N<sub>2</sub>O, CH<sub>4</sub>, NO<sub>x</sub>, NMVOC and CO. In addition, some biomass remains in the forest where it is transferred into dead organic matter pools (i.e., dead wood and litter), some of which decomposes quickly, returning carbon to the atmosphere, while the remainder can be stored for longer periods of time.

In this study the carbon sequestration from the aboveground biomass (i.e., tree tops and branches) has been taken into account and modeled. The below-ground biomass (i.e., tree stumps and roots) was explicitly excluded from the study.

The predominant forest type in the study region is industrial Douglas-fir plantation forest with an average rotation period of between 40 and 50 years. Accordingly, for this study the representative plot was assumed to be a Douglas-fir plantation forest with a rotation age of 45 years. The temporal carbon sequestration during forest growth was calculated using the Forest Vegetation Simulator (FVS). FVS is an empirical forest growth simulation model that represents different geographic areas across the United States. The model simulates forest growth in response to natural succession, disturbances and management actions. A simulation was run to generate results at five-year intervals using the Pacific Northwest Coast (PN) Variant.

The results of the model provide carbon stocks for standing and harvested biomass for the various tree components: stems, tops, foliage, branches, bark, roots and stumps. For this paper, the volume of standing carbon was calculated. The stem and bark volumes were attributed to logs while tops and branches were defined as residues.

The harvest residual biomass-based bioenergy from the tops and branches was selected for the analysis in this paper. The FVS simulation was run for a 45-year rotation period extending from 2014 to 2059. According to the IPCC Guidelines, the amount of CO<sub>2</sub> that is absorbed from the atmosphere and converted into biogenic carbon can be estimated by multiplying the difference in the carbon stocks (carbon sinks) between two subsequent years by the molecular weight of CO<sub>2</sub> and dividing this number by the molecular weight of carbon (IPCC 2006):

$$C_{seq} = \Delta C \cdot \frac{MW_{CO_2}}{MW_C}$$

where  $C_{seq}$  = carbon sequestered,  $\Delta C$  = difference of carbon stocks between two subsequent years,  $MW_{CO_2}$  = Molecular weight of CO<sub>2</sub> (44 kg/kmol), and  $MW_C$  = Molecular weight of carbon (12 kg/kmol) (IPCC 2006).

To incorporate the sequestered carbon into the LCA, the functional unit of wood has been tracked from the biomass growth in the forest through to its end of life. For this reason it is necessary to refer the total amount of carbon sequestration to the functional unit of the system by multiplying by

the ratio between the total amount of carbon dioxide corresponding to the harvested biomass and the amount of carbon dioxide corresponding to the functional unit. In this study the functional unit of analysis was 1 BDmT of wood, which was produced by harvesting 1.7 BDmT of trees, which equals 3.117 MgCO<sub>2e</sub>. The remaining 0.7 BDmT of biomass was harvest residues that are left in the forest to naturally decompose or be burned in a prescribed burn.

#### ***8.3.4 Harvest operations***

Forest operations include a combination of technologies and practices that differ from site to site based on the topography of the forest area and the type of forest management practice adopted. In this study, forest operations were categorized into five primary processes: 1) harvesting, 2) grinding and chipping, 3) secondary transportation, 4) loading, and 5) primary transportation. Data on harvest operations were used from the CORRIM Phase I and CORRIM Phase II reports (Bowyer et al., 2004; Lippke et al., 2010). Harvest operations consist of all the activities involved in cutting down a standing tree in the forest. Harvest operations in the PNW region often utilize the whole-tree harvesting method. This is an economically preferable method of harvesting trees that allows for the removal of limbs and tops at the harvest landing and reduces the requirements for subsequent slash disposal across the harvest site. Processing harvested trees at the landing include bucking, delimiting, and/or topping to remove the non-merchantable limbs and tops from the logs. Alternatively, lower-quality trees, including tops and branches, are often simply chipped entirely. Two primary products are obtained through these harvesting processes: logs and harvest residues. Logs are the primary product and they have the highest economic value. Normally, residues are not considered an important product since they have little economic value and are thus considered to be a waste material. However, in this study the harvest residues were the product of interest. The harvest residues (i.e., branches and tops of trees) are passed through a grinding or chipping machine that reduces them to a more compactable and transportable size. The grinder/chipper is fed from the slash piles located at the landing zone using a separate loader. The harvest residues are transported from the harvest area to a loading zone located near the forest road. This is a secondary transportation process that often consists of skidding the trees/residues on gentle slopes or yarding them on steep slopes. The residues are then loaded onto haul vehicles and are transported from the woods to a processing point (primary transportation).

Recovery of residue from sites in the mountainous PNW region faces physical restrictions, especially with respect to the road network required to haul the material. In most chipping and grinding operations, biomass material is transported on highways in 91.8-m<sup>3</sup> and 107.1-m<sup>3</sup> (120 or 140 cubic yard [CY]) chip vans. When these chip vans are attached to highway tractors, the combined units have a turning radius that exceeds the design radius of curves on the lowest standard of forest roads.



As a result, there are many forest sites where chip vans cannot access the log landings and therefore the biomass material must be shuttled from the landing using shorter-wheelbase dump trucks.

In this study the harvest residuals were ground/chipped at the primary landing location and shuttled in a dump truck to a secondary landing. It was assumed in this study that 65% of the harvest residuals (tops and branches) were transported to the primary landing while the remaining residuals were left scattered on the forest floor.

The data used for the LCA analysis related to the hourly consumption of diesel fuel and lubricants as well as the time of operation for the machines and transport trucks are summarized in Tables 8.1 and 8.2, respectively.

**Table 8.1** Hourly consumption of diesel and lubricants of machines and transport means used in forest operations.

Outputs 1 hr	Inputs	
	Diesel [l]	Lubricants [kg]
Front Loader	19.26	0.34
Large Whole Tree Chipper at Central Landing	68.55	1.07
Idle Engine 120CY chip van	8.33	0.13
Idle Engine 30 CY dump Truck	7.50	0.12
Shuttle (dump Tr) loose to central landing	23.73	0.81
Transport Chips to Facility (120 CY chip van)	37.85	0.59

**Table 8.2** Time of usage of machines and transport means used for forest operations per ton of woody biomass harvested.

Outputs 1 ton	Inputs
	Value [hr]
Front Loader	0.22
Large Whole Tree Chipper at Central Landing	0.02
Idle Engine 120CY chip van	0.02
Idle Engine 30CY dump Truck	0.37
Shuttle: dump truck (30CY); primary to central	0.33
Transport Chips to Facility (120 CY chip van)	0.18

Emission factors related to the fuel consumed and fertilizer used were developed from the SimaPro v.7.3 model, with an environmental impact analysis that utilized the TRACI2, v.3.3 method (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) developed by the US Environmental Protection Agency<sup>1</sup>.

As outlined previously, two products—logs and harvest residuals— were generated during the harvest process. When more than one product is produced by a single process, an allocation of the environmental impacts is required. Allocation is defined as: “Partitioning the inputs to, or emissions from, a shared process or a product system between the product system under study and one or more other product systems” (BSI, 2011). An allocation of impacts between the two products is required, which means that it is necessary to attribute energy and material flows to the products in different ratios based on a set of specific criteria. In general, there are two types of allocation systems used in LCA: mass allocation and economic allocation.

A mass allocation was used in this study, since the economic value of forest residuals is not well established. Impacts are allocated between the logs and residuals in relation to the percentage of the mass of each unit of wood extracted from the forest. Based on FVS model estimates, 80% of the above ground biomass is allocated to sawlogs (stem and bark) and 20% of the above ground biomass is allocated to harvest residuals (tops, branches and foliage).

### ***8.3.5 Residues left in the forest***

As previously noted, the assumption used in the study is that in order to produce 1 BDmT of biomass, 1.7 BDmT of residues needs to be harvested. In most forest operations, 0.7 BDmT of residual biomass is typically left behind on the forest floor as well as at the landing due to breakage/loss during the harvest, skidding and loading operations. Harvest residues left on the forest floor have an impact on the net emission profile since they decompose over time, releasing GHGs back into the atmosphere.

The dynamic decay of harvest residuals left on the forest floor depends on the physical characteristics of the timber species as well as the environmental conditions. These factors determine the rate of decay of the woody biomass and the ratio of biomass that decomposes versus that which remains in the forest, increasing the soil carbon. The composition of the emissions released depends on the chemistry of the reaction: if the reaction occurs under aerobic conditions, the biomass will decompose by reaction with oxygen, thereby releasing CO<sub>2</sub> into the atmosphere. If the reaction occurs under anaerobic conditions, CH<sub>4</sub> can be produced during decomposition, which substantially increases the impact on climate change. The decomposition of biomass left in forest follows an exponential decay function (EIA, 2006):

$$f(t) = Q \cdot e^{k(t-t_0)}$$

where  $f(t)$  = total biomass at time  $t$ ,  $Q$  = total biomass at time  $t_0$ , and  $k$  = decomposition rate ( $k = 0.021$  weighted value was used assuming 50% Douglas-fir, 25% ponderosa pine, 25% lodgepole pine (EIA 2006, Table 3.6).

The quantity of decomposed biomass over time equals the difference between the volume of biomass at time  $t$  and  $t_0$  and is evaluated through the derivative of the biomass decay function, which is expressed by the following equation:

$$f'(t) = k \cdot Q \cdot e^{k(t-t_0)}$$

where  $f'(t)$  = decomposed biomass.

It has been assumed that 90% of the biomass left in the forest decomposes over the reference time horizon, while 10% remains in the forest and contributes to an increase in the soil carbon. In addition, aerobic conditions have been assumed.

To evaluate the amount of CO<sub>2</sub> released into the atmosphere as the harvest residuals decay, it is necessary to convert the amount of decomposed biomass  $f'(t)$  to the amount of carbon by multiplying by 0.5 and then converting the amount of carbon to CO<sub>2</sub>.

### **8.3.6 Burning biomass**

At the end of these processes, the biomass is burned to produce energy for domestic heating and energy production. The burning of woody biomass emits a variety of gases and aerosols to the atmosphere, including carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), volatile and semi-volatile organic compounds (VOC and SVOC), particulate matter (PM), ammonia (NH<sub>3</sub>), sulfur dioxide (SO<sub>2</sub>) and methane (CH<sub>4</sub>) (Wiedinmyer and Neff, 2007), which significantly contributes to global warming.

Gases emitted during the combustion of woody biomass can affect air quality because they are responsible for the formation of global tropospheric ozone (O<sub>3</sub>). O<sub>3</sub> is formed by the oxidizing power of the hydroxyl radical (OH) that is produced by the photolysis of some oxygenated Non-Methane Organic Compound (NMOC) and O<sub>3</sub>, which reacts with carbon monoxide and NMOC (Akagi et al., 2010).

The IPCC global climate change report has linked most of these emissions with a variety of environmental problems, including climate change (IPCC, 2007). Thus, this study is focused on GHG emissions, as expressed in terms of the carbon dioxide equivalent. The values of emissions from burning biomass have been extracted from the NETL Life Cycle Inventory Data (NETL, 2013) and are reported in Table 8.3.

**Table 8.3** Emissions to air from the burning of 1 BDmT of biomass.

Substance	Comp.	Unit	Total
Carbon dioxide	Air	Mg	1.57
Methane	Air	Mg	2.03E-03
Carbon monoxide	Air	Mg	3.02E-02
NMVOG	Air	Mg	1.94E-03
Dust (unspecified)	Air	Mg	6.58E-03
Dust (PM 10)	Air	Mg	4.13E-03
Dust (PM 2.5)	Air	Mg	3.67E-03
Elemental carbon	Air	Mg	2.64E-04
Organic carbon	Air	Mg	1.98E-03
Nitrogen oxides	Air	Mg	2.50E-03
Ammonia	Air	Mg	2.21E-04
VOC	Air	Mg	2.57E-03
Sulphur dioxide	Air	Mg	8.30E-04
Methanol	Air	Mg	2.99E-04
Formaldehyde	Air	Mg	4.83E-04

### 8.3.7 Evaluation of the impact on global warming through radiative forcing

The dynamics of carbon uptake and release have been accounted for in the evaluation of the impact on global warming through the radiative forcing (RF) analysis, where a positive radiative forcing causes a warming effect on the system while a negative radiative forcing produces a cooling effect (IPCC 2007).

Radiative forcing is the product of the time-dependent abundance of the GHG by its radiative efficiency. The radiative efficiency is defined as the RF per unit mass increase in the atmospheric abundance of the GHG. The time-dependent abundance of the GHG is evaluated through the GHG decay functions of a pulse of emissions.

The impact on global warming of each GHG is then expressed in terms of the impact of CO<sub>2</sub> through the Global Warming Potential. The Global Warming Potential (GWP) index is based on the time-integrated global mean RF of a pulse of 1 kg of emissions of a component *i* relative to that of 1 kg of the reference gas CO<sub>2</sub>. The GWP of component *i* is defined by the equation (IPCC 2007):

$$GWP_i = \frac{\int_0^{TH} RF_i(t)dt}{\int_0^{TH} RF_r(t)dt} = \frac{\int_0^{TH} a_i[C_i(t)]dt}{\int_0^{TH} a_r[C_r(t)]dt}$$

where TH = time horizon, RF<sub>*i*</sub> = global mean RF of component

*i*, *a<sub>i</sub>* = RF per unit mass increase in the atmospheric abundance of component *i* (Radiative

Efficiency), and  $[C_i(t)]$  = time dependent abundance of  $i$  and the corresponding quantities for the reference gas ( $r$ ) in the denominator.

The decay function has been applied to the greenhouse gas emissions (carbon dioxide and other GHGs) for all phases of the life cycle assessment. The temporal aspect has been evaluated considering the cumulative value of emissions over the time period, which influences the radiative forcing. The decay of a pulse of GHGs ( $\text{CO}_2$  excluded) follows a first-order decay equation in the function of its lifetime in the atmosphere (IPCC 2007):

$$C(t) = e^{-\frac{t}{\tau}}$$

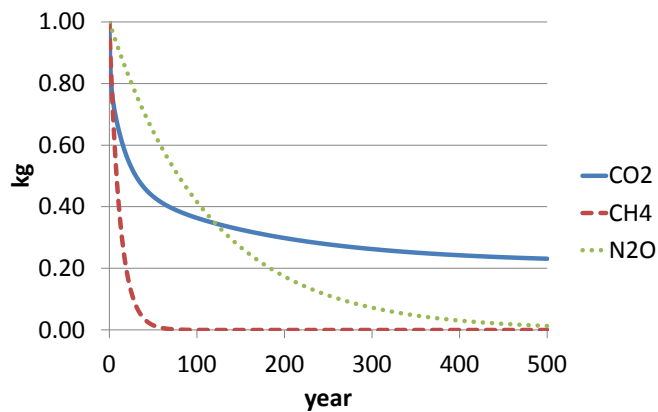
where  $\tau$  = lifetime ( $\tau = 12$  years for methane;  $\tau = 114$  years for nitrous dioxide).

The decay of a pulse of  $\text{CO}_2$  at time  $t$  is based on the revised version of the Bern Carbon cycle model and is given by (IPCC 2007):

$$a_0 + \sum_{i=1}^3 a_i e^{-t/\tau_i}$$

where  $a_0 = 0.217$ ,  $a_1 = 0.259$ ,  $a_2 = 0.338$ ,  $a_3 = 0.186$  and  $\tau_1 = 172.9$  years,  $\tau_2 = 18.51$  years,  $\tau_3 = 1.186$  years.

Applying the above equation to a unit of  $\text{CO}_2$ , the initial quantity of emissions is expected to decrease to 0.36 units after 100 years and to 0.23 units after 500 years. A residual of roughly 0.22 units is expected to remain in the atmosphere “for many millennia” (IPCC 2007), or even forever, if the underlying equation is assumed to be applicable for  $t = \infty$  (Müller-Wenk and Brandão, 2010). The decay rates for a unit-pulse of different GHGs are shown in Figure 8.3.



**Figure 8.3** Decay function of GHGs.

If the emission of GHG is not a pulse but it is released over time, then the decay function applies to any yearly release of emissions over the entire time frame. The integral can be approximated with the sum of the products of the time-dependent abundance of the GHG by its radiative efficiency:

$$RF_{cum} = \int_0^{TH} a_i \cdot [C_i(t)] dt \approx \sum_{i=0}^{TH} a_i \cdot [C_i(t)]$$

Also, if the emission is not unitary it is necessary to multiply the time-dependent abundance of the GHG by its annual emission and use the appropriate value of radiative efficiency:

$$[C_i(t)] = C(t) \cdot y_i(t)$$

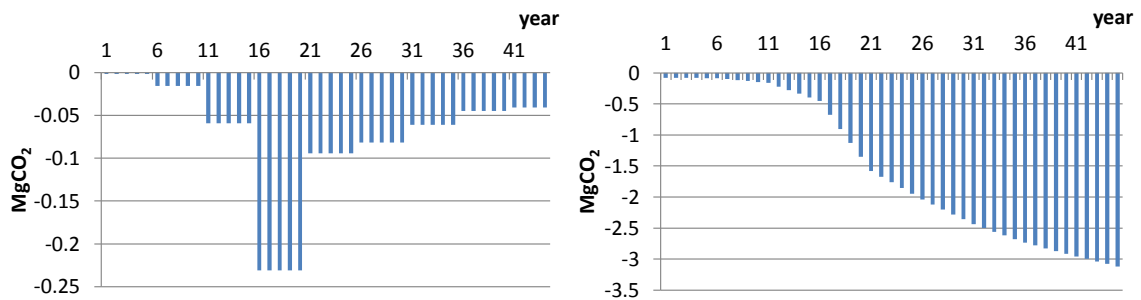
$$y_i(t) = a_0 + \sum_{i=1}^3 a_i e^{-\frac{t}{\tau_i}}$$

In the case of carbon sequestration, CO<sub>2</sub> is absorbed by the tree from the atmosphere. This process can be considered as a negative emission and its RF is negative. Also, the sequestered carbon has to be scaled back to the functional unit (1.7 BDmT of wood is harvested in order to produce 1 BDmT of biomass).

The methodology then has to be applied to the results of the LCA. The reference period is 100 years (as recommended by the ISO). The radiative efficiency for CO<sub>2</sub> has been assumed to be constant and equal to 1.8×10<sup>-15</sup> Wm<sup>-2</sup>·kg<sup>-1</sup> evaluated through the GWP. The radiative efficiency is a function of the greenhouse gas concentration in the atmosphere but it has been assumed to be constant based on the assumption that the emissions produced throughout the life cycle of the product do not significantly modify the overall global concentration of the greenhouse gases in the atmosphere.

## 8.4 Results

Our results have been calculated using the following emission and uptake considerations: 1) carbon sequestration, 2) forest operations, 3) biomass burn and 4) decomposition of harvest residues left on the forest floor and at the roadside landing. Figure 8.4 shows the carbon dioxide absorbed during the forest rotation period per functional unit based on the results of the FVS model.



**Figure 8.4** Difference of biomass growth between subsequent years (carbon sink) and carbon biomass (carbon stock) over time normalized to the functional unit (1 BDmT) expressed in terms of carbon dioxide absorbed.

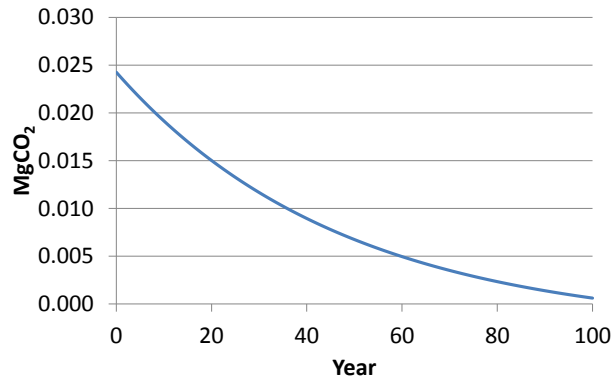
The results show that in the West Cascades region of the PNW, based on a rotation period of 45 years, the carbon dioxide absorption, as a result of biomass growth, reaches a maximum value between the 16th and 20th years.

The graphs were produced by normalizing the carbon sequestration to the functional unit, 1 BDmT of harvest residue delivered to the bioenergy facility. The results of the evaluation of the GHG emissions from the forest operations obtained from the SimaPro software are shown in Table 4. The total equivalent carbon dioxide is equal to 55.33 kgCO<sub>2</sub>e and is distributed between different GHGs as shown in Table 8.4.

**Table 8.4** Greenhouse gas emission from forest operations.

Substance	Comp.	Unit	Total
Carbon dioxide, fossil	Air	kg	53.47
Methane	Air	g	69.18
Methane, fossil	Air	g	4.94
Dinitrogen monoxide	Air	mg	41.97
Methane, dichloro-, HCC-30	Air	mg	357.22
Methane, dichlorodifluoro-, CFC-12	Air	mg	1.92
Ethane, 1,1,1-trichloro-, HCFC-140	Air	mg	1.55
Methane, tetrachloro-, CFC-10	Air	ng	191.83
Methane, monochloro-, R-40	Air	ng	98.58
Methane, bromo-, Halon 1001	Air	ng	29.76

The total emission from burning the biomass is equal to 1.62 MgCO<sub>2</sub>e. Both emissions from forest operations and burning biomass have been considered to occur at time zero, corresponding to the year when the biomass was harvested. Figure 8.5 represents the decomposition of the harvest residues left in the forest.

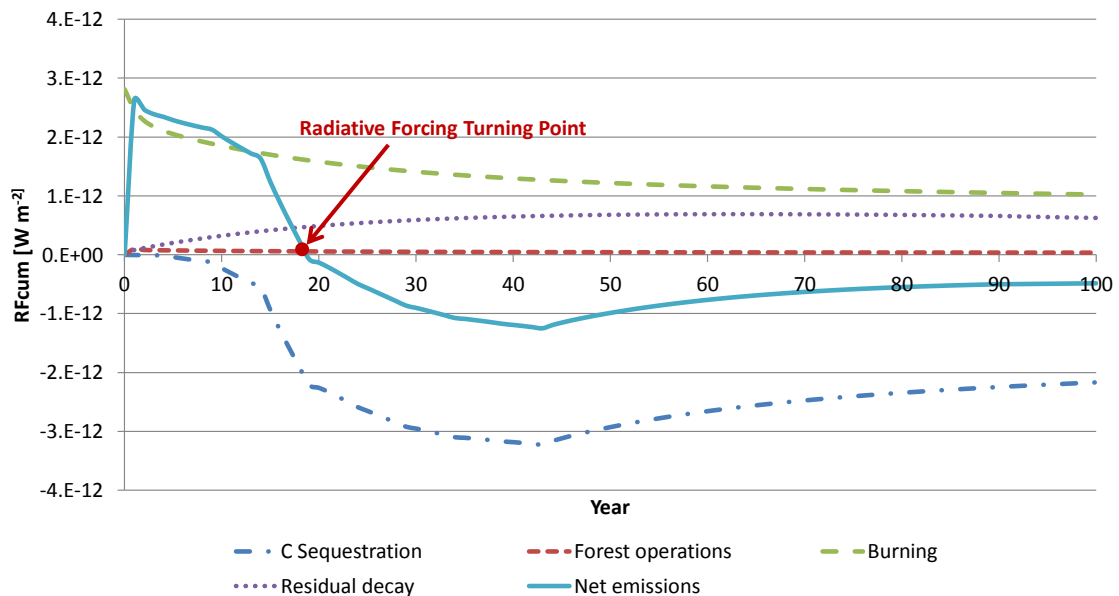


**Figure 8.5** *Decomposition of residues left in forest.*

Per functional unit, a total of 0.7 BDmT of residues are left in the forest to decompose. In this case carbon dioxide is slowly released over 100 years, which is included in the estimate of the global warming potential.

The results produced from the radiative forcing analysis are shown in Figure 8.6. Emissions that occur at time zero (i.e., forest operations and burning biomass) exponentially decay over time following the specific GHGs decay functions.

For removals and emissions that occur along different temporal paths (i.e., carbon sequestration and decomposition of residues) the result is a cumulative effect on radiative forcing that is specific for the dynamic obtained by applying the decay function of the emission at any time and summing the contributions. For the decomposition of harvest residues, the progressive reduction of the emission release is reflected by the cumulative radiative forcing function, which progressively reduces the rate of growth.



**Figure 8.6** *Result of the evaluation of the impact on global warming through the Radiative Forcing.*



For the carbon sequestration, the cumulative radiative forcing is the sum of the radiative forcing of a variable level of carbon dioxide sequestration over the rotation period. Our results show that a “Radiative Forcing Turning Point” exists. This is a point at which the positive cumulative radiative forcing of the emissions is fully offset by the cumulative negative radiative forcing of carbon sequestration. This study shows that the positive cumulative radiative forcing (global warming) associated with the emissions from forest operations, transportation, residue decomposition and biomass burning is compensated for by the negative radiative forcing (global cooling) of the carbon sequestration within 18 years. In other words, it takes just 18 years for the carbon sequestration within the forest to offset the carbon emissions generated by harvesting and burning biomass for energy.

This study also shows that carbon sequestration plays a significant role in the carbon balance and demonstrates the environmental benefits of using woody biomass-based bioenergy.

While the type of forest (species, biomass, rate of growth) and forest management system (rate of harvesting and silviculture) ultimately determine the level of environmental benefits, these benefits ultimately apply to all North American forest types.

## **8.5 Discussion**

The assumption of carbon neutrality, which is widely used in LCA studies, asserts that the impact of carbon emissions from woody biomass are completely offset by the benefits of carbon sequestration. Based on this assumption, the LCA accounting methods (as approved by ISO) ignore all biogenic carbon emissions from biofuels, resulting in favorable GWP numbers for woody biomass-based biofuels as compared to their fossil based counterparts. This study shows that using the dynamic LCA approach, under which the temporal nature of carbon sequestration and biogenic and non-biogenic emissions are all accounted for, also produces a favorable impact in terms of global warming.

This study outlined the crucial importance of introducing the temporal aspect in the LCA of bioenergy. For most of the products for which the LCA methodology is applied, the temporal aspect can be neglected without significantly changing the results because the life cycle of the product—from the production and acquisition of the raw materials, throughout the production, distribution and end of life—is completed in a relatively short period of time (e.g., mostly within one year). In the case of renewable energy, especially from woody biomass, the growth of the trees is based on the rotation period (ranging from 40 to 100 years), a period of time that is comparable with the time frame of evaluation of the impact on global warming.

For this reason, including the dynamic of forest growth into the LCA is of crucial importance and

can significantly influence the LCA results. This study highlights the fact that the global warming impact of using woody biomass for energy production is dependent on the type of forest management practice adopted and should be evaluated on a case-by-case basis.

The results of this study reinforce the importance of the time frame of the LCA-based environmental evaluation. On the one hand, the time frame of evaluation affects the values of the radiative efficiency and consequently the values of radiative forcing, and on the other hand the emissions or sequestration that occur many years after time zero will have different impacts on the evaluation based on the time frame of the study. For example, a GHG emission that occurs 90 years from time zero can have varying impacts, depending on whether the LCA time frame is 25 years, 100 years or 500 years, respectively (IPCC 2007).

As outlined by (Brandão et al., 2013) a very short time horizon would give too much weight to early GHG emissions (as well as to the first years of carbon storage or the first years by which emissions are delayed). Similarly, a very long time horizon would not take into account the urgency of the issue.

The limitations of this study are related to the exclusion of the below-ground biomass and soil carbon that influence the carbon balance. Furthermore, forest fires and other natural forest disturbances have not been taken into account. Forest fires have the potential of reducing the benefit of carbon sequestration on global warming because they significantly reduce the amount of above-ground biomass in the forest. Carbon sinks may also be partially compromised if the forest is subjected to natural disturbance. Thus, where data are available, a buffer should be taken into consideration to offset the possibility that a natural disturbance occurs (e.g., the risk of the spread of fires, the risk of parasite attacks, and the risk of breakage).

## **8.6 Conclusions**

In this study, the emissions generated through feedstock collection, biomass burning and the decay of forest residuals left in the forest were compared with the carbon sequestration achieved through biomass growth within the forest. The results clearly show that the adverse global warming potential impact associated with biomass collection and burning from industrial forests in the PNW region is fully offset by the carbon sequestered during forest growth within a period of approximately 18 years. Hence, for a given region and forest management and harvest practices, the carbon neutrality of woody biomass can be generally assumed.

This study also highlights the complexity associated with the carbon neutrality assumption of the woody biomass, especially in bioenergy end-uses. Here it should be noted that this study represents a plot-level analysis and not a regional analysis.

To be able to develop a comprehensive impact assessment of woody biomass-based bioenergy, a

regional assessment of the specific type of bioenergy needs to be conducted after factoring in the scale of production and the corresponding biomass supply zone.

### **8.7 Acknowledgements**

This work, as part of the Northwest Advanced Renewables Alliance (NARA), was funded by the Agriculture and Food Research Initiative Competitive Grant no. 2011-68005-30416 from the USDA National Institute of Food and Agriculture. The authors would also like to acknowledge the inputs and support provided by Mr. Tait Bowers and Mr. Jeffrey M. Connick of the UW's School of Environmental and Forest Sciences (SEFS) for their support in various phases of this study.



## Conclusions

In this research project a Life Cycle Assessment of wood products for bio-energy was performed. Two products were considered: firewood, which represents the main destination of the harvested wood in Italy; and wood chips, which are the most widely used material in biomass plants for both domestic and industrial use.

The Life Cycle Assessment of wood chips has outlined the environmental impacts of the forest operations of harvesting and processing as well as the impacts associated with the logistics.

Since the transportation was found to be the first source of greenhouse gas emissions throughout the life cycle, different scenarios were hypothesized, changing the transportation mean and the distance travelled in the different types of road, from the spur road to the Interstate road.

It was calculated that hauling the forest residuals in a larger roll off container (50CY capacity) instead than in a shuttle (30CY capacity) reduces greenhouse emissions by 39.8%.

Moreover changing the type of logistics the greenhouse gas emissions largely change. For example, increasing the miles of spur road from 2.5 to 3.5 to 5, and keeping constant the total mileage, the greenhouse gas emissions increase respectively by 11% and 27% compared to the base scenario. By contrast, increasing the miles of Interstate road from 75 to 100 to 120, the greenhouse gas emissions increase respectively by 6% and 10%.

This difference can be attributed to the higher consumption of fuels per unit of distance travelled in the spur road. Its irregular surface and the greater alternance of slopes and curves in fact sometimes cause peaks of fuel consumption and, as a consequence, of greenhouse gas emissions. On the contrary, the homogeneous straight field of the Interstate road favors a lower fuel consumption and, as a consequence, lower greenhouse gas emissions.

The Life Cycle Assessment of firewood allowed to evaluate what is the contribution of the long supply chain on the overall impact.

Moving from the short to the long supply chain the transportation of the raw materials represents the most important source of greenhouse gas emissions, with its contribution to the overall impact on global warming changing from 6.57% to 58.44%.

As far as the other impact categories are concerned, the combustion is the most critical phase.

In fact the combustion is responsible for the emissions of several pollutants which have an impact on a local scale (POCP and HTP).

These pollutants can be classified in four main categories: organic compounds, inorganic compounds, heavy metals and particles.

The impact on POCP is primarily determined by the emissions of carbon monoxide, as a result of incomplete combustion. The impact on HTP is due to the emission of polychlorinated dibenzo-p-dioxin (2,3,7,8-TCDD), benzene and formaldehyde. Furthermore heavy metals (arsenic, nickel

chromium, cadmium, lead) and fine and ultrafine particles ( $PM_{10}$  and  $PM_{2.5}$ ) are produced. It was found that the impact of the long supply chain is higher for global impact categories (GWP and ODP) than for local (POCP and HTP).

Therefore the transportation of the raw materials can be considered critical at different distances for different impact categories. For example for GWP and ODP these distances are respectively 229km and 41km; for POCP and HTP they are respectively 9754km and 5239km. Below those distances the combustion is the critical phase of the life cycle.

These results were discussed without taking into account the contribution of biogenic carbon dioxide. If the biogenic carbon dioxide was considered, surely the combustion would have been the first source of impact on GWP.

In traditional LCA this contribution is not taken into account based on the assumption of carbon neutrality, according to which the carbon dioxide released during combustion equals the carbon dioxide that was absorbed by the trees for the biomass growth.

In reality this approach does not consider that, while the carbon dioxide during combustion is instantaneously released in the atmosphere, the carbon dioxide which is absorbed for the biomass growth can take some decades depending on the rate of growth. Moreover also during the decomposition of wood in forest the carbon dioxide is slowly released over time.

These temporal discrepancy between carbon release and absorption can potentially have an effect on global warming. This effect was quantified through a “dynamic” Life Cycle Assessment through the Radiative Forcing. For removals and emissions that occur along different temporal paths the result is a cumulative effect on radiative forcing that is specific for the dynamic obtained by applying the decay function of the emission at any time and summing the contributions. The results show that a “Radiative Forcing Turning Point” exists. This is a point where the positive cumulative forcing is fully offset by the cumulative radiative forcing of carbon sequestration. This study shows that, in terms of impact on global warming, the emissions associated with the forest operations, the logistics, the decomposition of residues and the biomass burning are offset after 18 years (rotation period assumed equal to 45 years). After this point there is a net benefit on global warming.

Based on this findings, we could conclude that there is a net benefit on global warming in using wood products for bio-energy which depends on the forest management adopted. The carbon neutrality assumption could be adopted in a conservative way. However, this assumption underestimates the real benefit on global warming of the life cycle of woody bio-energy.

## **8.1 Innovative aspects of this study**

In this study the environmental impacts of wood products for bio-energy were evaluated in detail. The research project provides two case studies as practical examples of application of the methodology. Moreover a method is proposed, which has general validity and can be applied to every type of wood product.

This can be used not only to reproduce the two case studies but it can also be applied to wood products with different characteristics or scopes.

The third part of the study focuses on the development of the dynamic LCA. This is the result of the inclusion of the temporal aspects within the LCA through the Radiative Forcing. This aspect is very innovative in the LCA framework since there is no general consensus on how to deal with these aspects. Neither in LCA international standards nor in international politics this aspect has been introduced yet, although it is beginning to spark the interest of the scientific community.

Therefore even small variations in the results compared to the results of the traditional LCA could have enormous implications at global level, for the sharp increase that is expected to occur in the future in the use of biomass for the mitigation of climate change.

This approach would help to fix some unsolved problems in the LCA framework. In particular it can be applied to evaluate the impact of delayed emissions over time, topic of great importance both for evaluating the carbon stored in long lasting wood products and the delayed emissions for either natural decomposition or decomposition in landfill.

The methodology does not provide an univocal result for all types of biomass but allows to introduce specificities. In fact the type of site where the biomass is supplied from is important to determine its “sustainability”. The type of forest management significantly influences the impact on global warming as well as the residues quantity and the logistics. More research needs to be carried out to simulate different scenarios to understand how forest management can influence the sustainability of wood products. This aspect had not been considered before but the application of this approach could allow to define parameters in the international politics in favor of the types of biomass which has a higher benefit on the global warming considering the impacts of the overall supply chain. More research needs to be carried out about this topic to compare the dynamic LCA to the traditional LCA to quantify the variability in the results.

Lastly, the development of a software would to implement the calculation would allow to apply the method to a larger number of cases and to reduce the risk of human errors in the evaluation.





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