Science of the Total Environment 539 (2016) 45–60

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Environmental impacts of various biomass supply chains for the provision of raw wood in Bavaria, Germany, with focus on climate change

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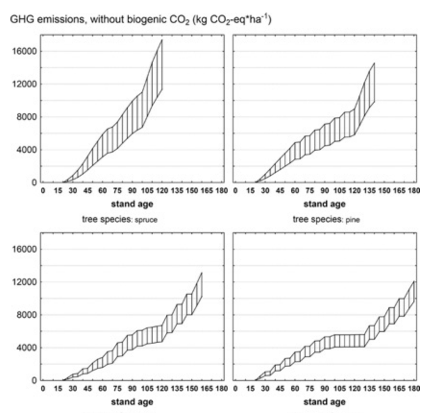
## HIGHLIGHTS

- There is a broad range of ghg-emissions caused by the provision of forest biomass
- Ghg-emissions are influenced by tree species, site quality or management intensity
- The most decisive factors are road maintenance, biomass harvesting and transport
- Ghg-emissions due to the provision of wood are small compared to its carbon stock

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 22 April 2015
Received in revised form 13 July 2015
Accepted 16 August 2015
Available online 6 September 2015

*Keywords:*
Forest management systems
Forest production
Greenhouse gas emissions
Life Cycle Assessment
Particulate matter
Primary energy consumption

## ABSTRACT

Wood biomass is considered a renewable raw product, but the supply chain of wood biomass involves non-renewable energy inputs, and thus possibly entailing environmental impacts. The objective of this study was to analyze different environmental impacts (GHG emissions, without biogenic $CO_2$; primary energy consumption, non-renewable; particulate matter) caused by the provision of forest biomass for the four main tree species in Bavaria using Life Cycle Assessment (LCA) techniques.

Based on forest growth simulations, a set of realistic forest biomass supply chains for Bavarian forestry conditions were modeled for the raw wood product system from site preparation to forest road and to plant/farm gate, respectively, analyzing the four different process groups: [A1] site preparation, [A2] site tending, [A3] biomass harvesting and [T] transport of biomass to plant/farm gate.

Total GHG emissions of about 383,000 t $CO_2$-eq $*$ year$^{-1}$ (18.95 kg $CO_2$-eq $*$ m$^{-3}$) are estimated for the Bavarian forestry sector (from site preparation to plant/farm gate) in the reference year 2013 indicating a share of 0.41% in the total GHG emissions of Bavaria. 0.035 MJ of non-renewable energy has to be invested in order to provide 1 MJ of woody biomass to plant/farm gate (267 MJ $*$ m$^{-3}$). One hundred and sixty six tons of particulate matter emissions per year are calculated for the Bavarian forestry sector in 2013 (0.008 kg $PM_{2.5}$-eq $*$ m$^{-3}$).

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http://dx.doi.org/10.1016/j.scitotenv.2015.08.087

Our LCA results reveal that there is no single GHG emission value for raw wood but a broad range of possible GHG emissions for the Bavarian forestry. Most decisive parameters are forest road maintenance, biomass harvesting, forwarding and biomass transport, and GHG emissions are also notably influenced by tree species, age class, wood assortment and site quality. We recommend that environmental impact calculations should be implemented, for example in wood certification procedures as they are important key indicators for sustainable forest management.



## 1. Introduction

For climate change mitigation, Germany aims to reduce greenhouse gas (GHG) emissions by 40% until 2020 and by at least 80% until 2050 compared to the levels of 1990 (Benndorf et al., 2014). The most important factor in this climate protection strategy is the reduction of energy consumption via an increased energy efficiency coupled with the reduction of non-renewable shares in the energy mix ("Energiewende"). Accordingly, Germany's targets are a share of renewable energy in the gross energy consumption of 18% in 2020 and of 80% in 2050 (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, 2014). Currently, renewable energies account for approximately 12% of the total final energy consumption in Germany (reference year: 2013, Federal Environment Agency, 2014). Besides renewable energies such as solar or wind power for the generation of power or fuel, energy from wood biomass is one of the core sources in order to fulfill the above mentioned targets, in particular for heating systems. For heating, wood biomass is the most important renewable source with a share of 12.5% in the total heat energy consumption in Bavaria (Bavarian State Office for Statistics, 2014).

Although wood biomass is considered a renewable energy source, it has to be taken into account that for the provision of wood and for subsequent transformation and conversion processes, non-renewable inputs are necessary, thereby modifying the assumption of a 100% renewable product. Although it is shown in various studies that the non-renewable input can be small in comparison to the energy content (e.g. in Berg and Lindholm, 2005) or to the carbon storage of wood (see literature study from Klein et al., 2015), holistic analyses of the total wood product chain are crucial in order to demonstrate and – if necessary – reduce the non-renewable input and thereby, environmental impacts due to the provision of raw wood and the production of wood products.

For analyzing environmental burdens of products, the Life Cycle Assessment (LCA) method is a useful and established approach. Following the EN ISO 14040 (2009) definition, a LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle system", indicating that the LCA is suitable to identify plenty of environmental impacts. The impact on climate change, which is apparently the most common LCA impact category, is just one of a manifold set of possible categories including also, for example, non-renewable energy consumption, particulate matter or land use. Finally, the choice of impact categories depends on the goals of the study.

In recent years, a variety of LCA studies for different biomass sources has been published, for example for short rotation tree species as shown in the review study of Djomo et al. (2011), for bioenergy systems (Cherubini and Strømman, 2011) or for raw wood, summarized for example in Klein et al. (2015) or Heinimann (2012). Several review studies report concordantly that the diversity concerning the methodical approaches, the completeness of studied systems or the presentation of LCA results of existing studies often hamper comparisons between different biomass supply chains. Furthermore, it was found that the amount of LCA studies on the provision of forest biomass has been steadily increasing over the last years. However, the number of studies is still small and there is still a lack of knowledge concerning several issues (e.g. relevant processes or system boundaries) of the LCA of forest biomass supply chains (Klein et al., 2015). As indicated above, harmonized methods have to be developed to make studies comparable. Additionally, more detailed descriptions of results for specific forest biomass supply chains are still required, as it was shown that GHG emissions are within a broad range and a universal value for all realistic supply chains cannot be assumed (Klein et al., 2015).

However, several LCA studies were conducted for the forestry sector in the last years, primarily dealing with the GHG emissions of raw wood for some country-specific forest biomass chains in Europe, for example for Norway (Timmermann and Dibdiakova, 2014), Portugal (Dias, 2014), Ireland (Murphy et al., 2014) or Finland (Routa et al., 2013) or for some special regions such as the alps in Italy (Mirabella et al., 2014; Valente et al., 2011). Existing LCA studies are not only focused on European forests but also applied outside Europe, in particular in the US (e.g. Sonne, 2006; White et al., 2005) but also in other countries, for example Ghana (Eshun et al., 2010) or Japan (Kinjo et al., 2005).

For wood biomass supply chains in Germany, some basic studies are available from the 1990ies (Frühwald and Wegener, 1993; Zimmer and Wegener, 1996; Schweinle, 1997) and recently some more studies have been published, for example one for Douglas-fir round wood (González-García et al., 2013), one study with focus on forwarding of raw wood to forest road (Engel et al., 2012) or one study with LCA of forest raw wood as part of a holistic wood product chain (Albrecht et al., 2008). However, studies for the entire forest system from site preparation to plant/farm gate analyzing different biomass supply chains based on, for example different site conditions or management intensities are still rare for German or Bavarian forest conditions, respectively.

In Bavaria, forests cover about 37% of the entire land area with a gross forest area of about 2.6 Mio ha and a total growing stock of 990 Mio $m^3$ (Klemmt et al., 2014). The four most important tree species (Norway spruce, Scots pine, Common beech and Oak spec.) cover almost 80% of the total forest area and comprise more than 85% of the total timber volume. The mean annual timber volumes between the last two National Forest Inventories (NFI) in 2002 and 2012 were 28.1 Mio $m^3$, of which spruce accounted for the highest share (70%). According to the national timber statistics, half of all volumes (51%) were dedicated to round wood, 9% to industrial wood and 40% to energy wood, the latter one was dominated by split logs (Gaggermeier et al., 2014). NFI results for Bavaria also reveal that total harvested timber volumes did not exceed volume increment rates. However, the demand for wood, especially for energetic purposes, is increasing, among others due to the above mentioned German energy policies. As such, the share of energy wood in the total harvested wood volumes has increased from 3.7 Mio tons in 2005 to 6.2 Mio tons in 2012 in the last years in Bavaria (Gaggermeier et al., 2014). As wood use is one important factor in the climate change mitigation strategy of Bavaria, especially due to the use of wood for energetic purposes, it is crucial to analyze and understand the environmental impacts of the provision of raw wood as it is the first step of several wood product chains. Therefore, the present study aims to respond to the following questions:

(1) In which order of magnitude causes the provision of raw wood from typical Bavarian forest stands environmental impacts concerning the categories climate change, primary energy consumption and particulate matter?