Journal of Cleaner Production 66 (2014) 188–198

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Cradle-to-gate Life Cycle Assessment of forest operations in Europe: environmental and energy profiles

Sara González-García [a,*], María Teresa Moreira [b], Ana Cláudia Dias [a], Blas Mola-Yudego [c]

[a] CESAM, Department of Environment and Planning, University of Aveiro, 3810-193 Aveiro, Portugal
[b] Department of Chemical Engineering, Institute of Technology, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain
[c] School of Forest Sciences, University of Eastern Finland, PO Box 111, FI 80101 Joensuu, Finland

ARTICLE INFO

Article history:
Received 28 May 2013
Received in revised form
21 October 2013
Accepted 19 November 2013
Available online 3 December 2013

Keywords:
Douglas-fir
Maritime pine
Norway spruce
Poplar
Wood biomass
Willow plantations

ABSTRACT

Life Cycle Assessment (LCA) has become a common and standardized methodology to evaluate the environmental profiles of forest systems. In this study twelve different European forest systems dedicated to wood production for industrial or energy uses (maritime pine, spruce, willow, poplar and Douglas-fir) were compared in detail from environmental and energy points of view considering a cradle-to-gate perspective. The scenarios included the silviculture of these tree species in Sweden, Germany, France, Italy and Portugal. A database with inventory data was constructed for each scenario. The scenarios considered were standardized using the same methodological life cycle assumptions in order to establish comparisons for an overall analysis.

The results show a relatively wide range of variations in terms of biomass productivities as well as environmental and energy profiles. These variations depended on the tree species, management regime (different levels of fertilization, time of harvesting and intensity of forest operations) and the overall conditions of the location of the plantations. However, regardless of the scenario considered, operations related to logging such as harvesting and forwarding were identified as *hotspots* mainly due to the remarkable fuel requirement. Fertilization activities and fertilizer production (when required), thinning processes (when necessary) as well as weed control related processes reported also notable contributions to the categories under assessment.

If these twelve scenarios are compared with other similar studies for the same tree species, significant differences can be found which are mainly linked to different forest management regimes and regional characteristics.

The choice and the promotion of a specific forest biomass for industrial applications should not only depend on the biomass yield and the harvesting age but it should be also based on the intensity of forest practices since it considerably affects the environmental and energy profiles.

1. Introduction

Life Cycle Assessment (LCA) is a standardized methodology to assess the environmental aspects and potential impacts associated with a product, process or activity from a life cycle perspective (ISO, 2006). This is an extended method with a holistic approach which guarantees the comprehensiveness of an environmental evaluation, assuring its reproducibility (ISO, 2006).

The application of LCA methodology for evaluating the environmental consequences of production systems has been performed for a diverse range of sectors such as the dairy sector (Iribarren et al., 2011; González-García et al., 2013a), the fishery sector (Hospido et al., 2006; Vázquez-Rowe et al., 2010), the agricultural sector (Vázquez-Rowe et al., 2013) or the biofuels sector (González-García et al., 2010, 2012a; Dressler et al., 2012).

To a certain extent, the forest sector has been at the vanguard in operationally implementing the concept of sustainability along the years in order to introduce the indicators for sustainable forest management (Berg et al., 2012). About 35% of the total European land area is occupied by forests and wooden land (European Commission, 2010), although the European forest sector is characterized by a large diversity of forest types, management alternatives, site productivity and socio-economic conditions including ownership structure (Berg et al., 2012).

The analysis and quantification of environmental impacts derived from the forest sector has been the focus of attention in

* Corresponding author. Tel.: +351 234370387.
E-mail addresses: sara.gez.garcia@gmail.com, saraggarcia@ua.pt, sara.gonzalez@usc.es (S. González-García).

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http://dx.doi.org/10.1016/j.jclepro.2013.11.067

recent years, and it already exists extensive academic literature on the field, related not only to forest activities oriented to wood production (González-García et al., 2009a, 2009b; Berg et al., 2012) but also wood processing to obtain wood based products such as boards (Rivela et al., 2007; González-García et al., 2009c), paper pulp (González-García et al., 2009d), writing paper (Dias et al., 2007), floor coverings (Petersen and Solberg, 2003; Nebel et al., 2006) or furniture (González-García et al., 2011).

In this context, forest operations are considered as key activities in related wood based industries in terms of environmental and economic perspectives (Berg et al., 2012). In fact, the wood is the main renewable resource used to produce both wooden products and energy. Thus, special attention must be paid on the operations performed in plantations in order produce the raw material under a more environmental friendly system.

When considering the target species for the environmental assessment, it is important to take into account the scheme of forest management, the productivity, the wood use as well as the environmental effects (e.g. acidification, eutrophication or global warming) associated to silviculture.

Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) are commonly planted in Scandinavian countries for paper pulp production. Maritime pine (*Pinus pinaster*) is a common industrial tree species in the Iberian Peninsula (Spain, Portugal and South France). In the case of Spain and Portugal, it is an extended species together with Eucalypt (Berg et al., 2012; Dias and Arroja, 2012), providing almost all the wood biomass for paper pulp production. Douglas-fir is a coniferous species which has an increasing importance in European countries such as Germany and France in recent years due to its high productivity (Heidingsfelder and Knoke, 2004) and its large physiological adaptability (Albrecht et al., 2012). In addition, Douglas-fir biomass presents very good mechanical and processing properties, being a favourable raw material for outdoor wood based elements and construction materials (Kutnik et al., 2011).

Regarding energy production, the use of wood biomass is gaining increasing interest worldwide as a means of meeting regional demands for heat and electrical power generation. Willow (*Salix* spp.) and poplar (*Populus* spp.) are fast growing species whose cultivation is very extended in Europe, mainly for energy purposes, but also wood products, geotextiles and pulp production (Venturi et al., 1999). Sweden is the European leader in short rotation (SR) willow plantations (González-García et al., 2012b) while poplar is much extended in Italy (Fiala and Bacenetti, 2012) specifically in the northern regions.

This paper aims to compare forest management activities carried out in Europe using the LCA approach in terms of fossil fuels requirement and four impact categories (global warming, photochemical oxidants formation, eutrophication and acidification. Thus, this study intends to give an overview of European current forest practices with industrial application performed nowadays as well as to orientate forest based industries towards the use of alternative wood biomass sources. Differences on forest practices intensity, lifespan and system boundaries make the comparison of environmental profiles difficult. For this reason and in order to allow a direct comparison of wood biomass, representative forest tree species were assessed up to the forest gate (cradle-to-gate perspective), excluding further activities (processing and transport) from the assessment. Therefore, this study will compare the environmental impacts associated with forest practices of Norway spruce stands and willow plantations in Sweden, Douglas-fir plantations in Germany and France, maritime pine stands in Portugal and France and poplar plantations in Italy. Therefore, the study comprises different forest tree species in an extensive European area.

2. Materials and methods

2.1. Methodology

LCA evaluates the environmental burdens by identifying resource and energy consumptions as well as emissions to different environmental compartments resulting from the particular life cycle, including opportunities in order to identify priority areas where improvement actions will have the greatest effects on reducing environmental impacts (ISO, 2006).

2.2. Goal and scope definition and selection of the functional unit

The present study aims at the analysis and comparison of environmental profiles associated with the production of wood biomass for five representative tree species for different industrial uses (wood products and energy): willow (Salix sp.), poplar (*Populus* sp.), maritime pine (*Pinus pinaster*), Douglas-fir (*Pseudotsuga menziesii*) and spruce (*Picea abies*) in a number of European countries (from north to south: Sweden, Germany, France, Portugal and Italy).

The locations and species analysed were subject to an initial analysis in order to define scenarios with different forest management operations. Datasets for each scenario were collected from previous LCA studies, including González-García et al., 2009a; Dias and Arroja, 2012; González-García et al., 2012b, 2013b; 2012c; 2013c. All forest scenarios were harmonized in terms of inventory data, methodological assumptions (system boundaries, databases and impact assessment method) and functional unit in order to achieve a valid comparison. As the purpose of this LCA study was to determine and compare differences between forest management scenarios for different species and countries, the functional unit was thus defined as 1 m^3 of felled fresh roundwood per year ($m^3 \cdot year^{-1}$), as it reflects not only differences on the biomass productivity and growing rate but also on the soil composition and climatic characteristics. In order to standardize the units, information concerning lifespan, productivity and moisture content of wood was collected (Table 1).

2.3. Description of the system boundaries

In total, twelve different forest management scenarios were compared considering the same system boundaries and assumptions (i.e. background processes, wood biomass yield and infrastructure construction and maintenance) for the different production regimes Fig. 1. The scenarios corresponding to the production of wood biomass from Douglas-fir, poplar and willow were based on commercial plantations located in France, Germany, Italy and Sweden. Concerning the production of wood biomass from maritime pine and spruce were based on forest stands located in France, Portugal, and Sweden.

The comparisons were performed from a cradle-to-gate perspective: i.e., from the extraction of raw materials through the management operations up to the loading of the wood biomass onto trucks at road site. Thus, the rest of the supply chain to the corresponding processing facility was excluded from the system boundaries. Therefore, all forest operations performed throughout their lifespan were identified, inventoried and assessed (Fig. 2).

The scenarios were divided into three subsystems or stages: Site preparation (S1), Stand establishment and tending (S2) and Logging operations (S3) Activities related with the construction and maintenance of infrastructure (road and firebreak) were excluded from the system boundaries due to the lack of information in willow, spruce and poplar related scenarios. However, and according to the literature for other forest species such as maritime pine (Dias