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Environmental life cycle assessment of producing willow, alfalfa and straw from spring barley as feedstocks for bioenergy or biorefinery systems

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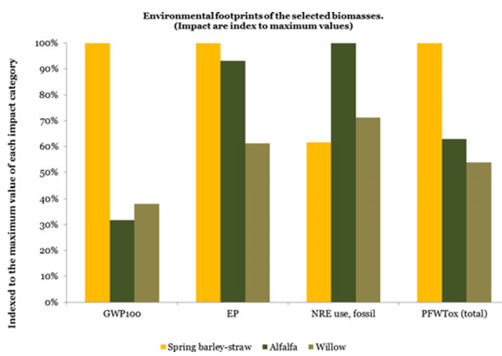
HIGHLIGHTS

- Both annual and perennial crops were considered for the assessment.
- Emission due to SOC change was calculated from net C input to soil.
- SOC stock change was set as an indicator for the assessment on soil quality.
- Carbon footprint was lowest in alfalfa and willow.
- Straw had lower Non-Renewable Energy use than rest of the biomasses.
- Higher energy output to input ratio was for willow compared to alfalfa and straw.

GRAPHICAL ABSTRACT



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ABSTRACT

The current study aimed at evaluating potential environmental impacts for the production of willow, alfalfa and straw from spring barley as feedstocks for bioenergy or biorefinery systems. A method of Life Cycle Assessment was used to evaluate based on the following impact categories: Global Warming Potential (GWP_{100}), Eutrophication Potential (EP), Non-Renewable Energy (NRE) use, Agricultural Land Occupation (ALO), Potential Freshwater Ecotoxicity (PFWTox) and Soil quality. With regard to the methods, soil organic carbon (SOC) change related to the land occupation was calculated based on the net carbon input to the soil. Freshwater ecotoxicity was calculated using the comparative toxicity units of the active ingredients and their average emission distribution fractions to air and freshwater. Soil quality was based on the change in the SOC stock estimated during the land use transformation and land occupation. Environmental impacts for straw were economically allocated from the impacts obtained for spring barley. The results obtained per ton dry matter showed a lower carbon footprint for willow and alfalfa compared to straw. It was due to higher soil carbon sequestration and lower N_2O emissions. Likewise, willow and alfalfa had lower EP than straw. Straw had lowest NRE use compared to other biomasses. PFWTox was lower in willow and alfalfa compared to straw. A critical negative effect on soil quality was found with the spring barley production and hence for straw. Based on the energy output to input ratio, willow performed better than other biomasses. On the basis of carbohydrate content of straw, the equivalent dry matter of alfalfa and willow would be requiring higher. The environmental impacts of the selected biomasses in

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biorefinery therefore would differ based on the conversion efficiency, e.g. of the carbohydrates in the related biorefinery processes.

1. Introduction

Increasing demands for food, feed, fibers and energy from the available agricultural land has stressed to optimize the biomass productions from the available land. It has also stressed to explore sustainable opportunities for the combined production of fuels, food/feed and chemicals (Parajuli et al., 2015a). Biorefineries thus evolved to bring new value chains in the biomass conversion by producing cascades of biobased products. The types of biomass used is additionally important for their sustainable conversion to biofuels (Caputo et al., 2005), since their different chemical composition (e.g., carbohydrate content) affecting the biochemical conversions (Stephen et al., 2012). One of the crucial challenges for sustainable biorefinery operation is maintaining a year-round supply of biomass (Cherubini et al., 2007). This is relevant as over exploitation of biomasses would be on: soil carbon (C) sequestration (Fargione et al., 2008), nitrous-oxide emissions (Crutzen et al., 2008), nitrate pollution (Donner and Kucharik, 2008), biodiversity (Landis et al., 2008) and human health (Hill et al., 2009). Likewise, soil quality is crucial for the long-term productivity of agricultural soil and also for the provision of other ecosystem services (Milà I Canals et al., 2007a). Soil quality is often assessed in terms of soil organic carbon change and fertility (Lal, 2015). Likewise, sustainable management of available resources is also pertinent. Estimates show that about 10–20% of existing grassland within the EU member states, approximately 16.4 million hectare (Mha), is available for alternative uses to animal feed production (Mandl, 2010). These have stressed to diversify the supply of biomass to different biorefinery systems so that sustainable production of both fuel and non-fuel products is possible.

Life Cycle Assessment (LCA) has been widely used as a tool for assessing the environmental sustainability of different production systems (European Commission, 2015). Most of the LCA studies related to biomass production system have mainly focused on greenhouse gas (GHG) balances. In order to select the right biomasses and processing methods, it is also necessary to evaluate other impact categories besides GHG and energy balances (Wagner and Lewandowski, 2017). These are helpful to avoid creating flawed decision support tools for biorefining policies that may occur if evaluations are based on a single indicator (Finkbeiner, 2009). In most of the LCA studies, combinations of different crops including annual and perennial grasses were partially covered and described. Mogensen et al. (2014) quantified the impacts of producing different crops for livestock production, but mainly focused on the carbon footprint. Likewise, Pugesgaard et al. (2013) compared the energy balance and nitrate leaching of annual crops and grasses in a rotation. Impacts of Soil Organic Carbon (SOC) on the GHG balance was also partially addressed in most of the identified studies (Tonini et al., 2012). In a study of Short Rotation Coppice (SRC), Dillen et al. (2013) focused on energy balance, but assumed a less intensified farming system. Similar studies on SRC include Goglio and Owende (2009), Pugesgaard et al. (2015) and Sabbatini et al. (2015), but they were based on different assumptions with regard to farming system. Gallego et al. (2011) was limited for not covering SOC change in the overall GHG balances of alfalfa production. Godard et al. (2013) compared six feedstock supply scenarios, but the emission factors and other basic assumptions adopted in their modeling were less consistent with our study, particularly regarding system boundary and the agro-climatic conditions. Wagner and Lewandowski (2017) included a wide range of impact categories in their study, but it seemed that the system boundary for the related emissions was differently used, e.g. for the calculation of freshwater ecotoxicity. Birkved and Hauschild (2006) suggested that emissions of pesticides to soil can occur indirectly, hence it is relevant to assess the relative emissions to air and freshwater. Parajuli et al. (2016) using the tool PestLCI 2.0.6 presented the sensitivity of using different types of pesticides and varying agro-climatic parameters on the emission distribution fractions of the active ingredients. Based on their study, ecotoxicological measures were sensitive to the types of active ingredients and the season of applying the pesticides, as also coined in similar line in Dijkman et al. (2012).

Environmental sustainability assessments of the biomass production is one of the first steps to be taken for ensuring sustainable diversification in their supplies and the conversions (Parajuli et al., 2015a). In this study, LCA is used for evaluating the environmental footprints of producing willow, alfalfa and straw from spring barley. The biomasses were selected on the basis of their different physiochemical and environmental qualities (Parajuli et al., 2015b). Higher cellulose to lignin ratio in straw and willow can be regarded as a quality that qualifies them for sugar-based biorefinery platforms. Likewise, the crude protein and carbohydrate contents of alfalfa make it suitable for a green biorefinery technology to produce green protein and other biochemicals (e.g. lysine, lactic acid) (Parajuli et al., 2015b). Straw is regarded to induce a lower land use competition compared to other feedstocks (Kim and Dale, 2004). Willow, in turn, is suited for cultivation on marginal land, reducing its competition with food crops grown on fertile land (Helby et al., 2004). Willow also has an effective nutrient uptake from soil, lower GHG emission and better fossil fuel energy balance compared to fossil fuels (Murphy et al., 2014). The current study hence aims at evaluating different types of biomass feedstocks taking into account the important environmental impact categories.

2. Materials and methods

2.1. Goal, system boundaries and functional unit

The primary goal of this study is to provide a holistic view of resource requirements, emissions and finally evaluating environmental impacts for the production of the selected biomasses for utilizing them as bioenergy or biorefinery feedstocks. For this purpose, we take into account the system-wide effects of resource utilization starting from material extraction, processing, production and their utilization in an agricultural system. The system boundaries for the production of the selected biomasses are shown in Fig. 1. The system boundaries covered: (i) the background system (upstream processes) and (ii) the foreground system (downstream processes). The background system included the production of the assumed material inputs (e.g. fuel, chemicals, and agricultural machinery) and their supply to the foreground system. All the necessary data related to the background system were based on Ecoinvent 3 (Weidema et al., 2013), unless otherwise stated in the text below. Foreground system included