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Life cycle assessment of the integrated generation of solid fuel and biogas from biomass (IFBB) in comparison to different energy recovery, animal-based and non-refining management systems

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ABSTRACT

The study compares energy production from semi-natural grasslands by the integrated generation of solid fuel and biogas from biomass (IFBB) through mechanical separation of the biomass with the dry fermentation (DF) and hay combustion system (HC). In addition, traditional use for beef cattle production and non-refining systems of landscape conservation, i.e. mulching and composting, are considered. Highest conversion efficiency (45–54% of the gross yield), net savings of fossil fuels (44–54 GJ ha^{-1}) and net savings of greenhouse gases (2.9–3.7 t $CO_{2\text{-eq}}$ ha^{-1}) are obtained by HC and IFBB. Potentials of DF are limited due to low digestibility of the mature biomass.

1. Introduction

Due to their particular importance for biodiversity and landscape conservation, semi-natural grasslands strongly depend on the continuation of extensive agricultural practice (Halada et al., 2011). However, in many European regions an increasing abandonment of high-value grasslands has been observed over the past decades as a consequence of low economic return from grazing and forage production (Rösch et al., 2009). European nature conservation schemes and also local agricultural environmental programmes have been established aiming at the maintenance of an adapted management of the designated high-value vegetations, but they did not prove to be a sufficient framework to reduce the decline of semi-natural grasslands (Strijker, 2005). Recent evaluations of the situation of European high-value grassland have clearly stated the need to strengthen the measures to maintain the status of these sites (EC, 2009).

Apart from future strategies to improve the profitability of animal-based management of semi-natural grasslands, the use of grassland biomass for energy recovery has become increasingly relevant against the background of limited fossil energy resources, climate change and rising competition of food and energy crops on arable land (Prochnow et al., 2009; Tilman et al., 2006). Compared to biomass from high-yielding and intensively managed sites, semi-natural grasslands are highly diverse in plant and nutrient composition and rich in fibre content due to the delayed cut and, hence, have special demands on the technique used for conversion into energy carriers. Technical and economic constraints such as low anaerobic digestibility of the silage when used for biogas production as well as high proportions of minerals, nitrogen and sulphur affecting the thermal use of hay have been the main impediments to the exploitation of semi-natural grasslands for energy production up to now (Obernberger et al., 2006; Richter et al., 2009).

The present study aimed at the comprehensive assessment of a technological approach to producing energy from semi-natural meadows following the integrated generation of solid fuel and biogas from biomass (IFBB) (Wachendorf et al., 2009). The core element of this conversion system is the mechanical dehydration of the biomass after hydro-thermal conditioning. The main product is a solid fuel with improved combustion characteristics due to

Abbreviations: AST, ash softening temperature; BC, beef cattle; CHP, combined heat and power plant; CO, composting; DF, dry fermentation; DM, dry matter; HC, hay combustion; HHV, higher heating value; IFBB, integrated generation of solid fuel and biogas from biomass; IFBB-AO, IFBB-add-on system; IFBB-SA, IFBB-stand-alone system; LCA, life cycle assessment; LHV, lower heating value; l_N, normal litre; ME, metabolisable energy; MU, mulching; NfE, nitrogen-free extract; oADF, acid detergent fibre; oADL, acid detergent lignin; oM, organic matter; oNDF, neutral detergent fibre; tkm, tonne-kilometre; XF, crude fibre; XL, crude fat; XP, crude protein.

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lower mineral content compared to the untreated biomass (Wachendorf et al., 2009). The resulting liquid is used for biogas production with a high degree of digestibility (Richter et al., 2009). The study was conducted according to the principles of life cycle assessment (LCA), considering the impact categories of conversion efficiency, non-renewable primary energy and greenhouse gas balance, as well as the acidification and eutrophication balance (DIN, 2006). Beside the assessment of the IFBB system, alternative energy systems (dry fermentation, hay combustion), an animal-based system (beef cattle husbandry) and non-refining systems (mulching, composting) have been evaluated to cover alternative management options that are in principle appropriate for maintaining the management of semi-natural grasslands. The study investigated (i) energy fluxes and conversion efficiency of the energy recovery systems, (ii) the performance of energy recovery systems in terms of non-renewable primary energy and greenhouse gas savings, as well as acidification and eutrophication potentials and (iii) the extent to which energy recovery systems differ from animal-based and non-refining systems, considering greenhouse gas, acidification and eutrophication balance.

2. Methods

The study was based on the principles of LCA methodology according to DIN EN ISO 14040 (DIN, 2006) providing a comprehensive analysis of the energy and environmental performance of a production system. It evaluated and compared seven management and utilisation systems of semi-natural grasslands: (1) energy recovery by the IFBB technology as a stand-alone system (IFBB-SA), (2) energy recovery by the IFBB technology as an add-on system to an agricultural biogas plant (IFBB-AO), (3) energy recovery by dry fermentation (DF), (4) energy recovery by hay combustion (HC), (5) animal-based utilisation by beef cattle husbandry (BC), (6) mulching of the grassland (MU) and (7) composting (CO) (Fig. 1). The following sections show the conceptual framework of the study, the parameters, the assumptions made and descriptions of the systems.

2.1. Biomass feedstock

The present study was focused on semi-natural grassland swards which were established over a long period by regular grass-cutting and hay-making and which potentially are threatened by rural activity abandonment. Data used for the LCA referred to the average values of a broad evaluation of 18 European semi-natural grasslands (three sub-plots per area) in Germany, Wales and Estonia investigated within the European project PROGRASS. Regressive models (using SigmaPlot 9.0 Software) and analysis of variance (using R Software) were conducted by the data set of $n = 54$. The data set comprised most important habitat types of mowing management according to NATURA 2000 classification, which are listed in the Council Directive on the conservation of natural habitats and of wild fauna and flora and which are available in the particular countries. The gross biomass yield was 3.8 t DM ha^{-1} yr^{-1} resulting from a late cut in July. Data on the chemical composition of the biomass can be found in Table 1. Each scenario referred to biomass use from 500 ha, corresponding to an annual turnover of 1925 t DM with an average farm-to-field distance of 5 km.

2.2. Impact categories

The assessment was focused on the impact categories (1) conversion efficiency, (2) non-renewable primary energy balance, (3) greenhouse gas balance, (4) acidification balance and (5) eutrophication balance. These impact categories are most frequently used to characterise agricultural energy recovery systems, as they allow conclusions on the potential for saving fossil resources and for mitigating climate change, but also evaluate the negative impacts on air quality (Cherubini and Strømman, 2011). The greenhouse gas balance was based on the emissions of the three most important greenhouse gases carbon dioxide, methane and nitrous oxide over a 100 year time horizon and their global warming potentials, in accordance with the Intergovernmental Panel on Climate Change (expressed as carbon dioxide equivalents, $CO_{2\text{-eq}}$) (Forster et al., 2007). In terms of environmental concerns in soils, water bodies and atmosphere, the assessment of the acidification potential was implemented considering the emissions of sulphur dioxide, nitrogen oxides, ammonia and hydrogen chloride (expressed as sulphur dioxide equivalents, $SO_{2\text{-eq}}$). Regarding the eutrophication potential, emissions of nitrogen oxides and ammonia (expressed as phosphate equivalents, $PO_{4\text{-eq}}$) were taken into account.

2.3. Functional unit and system boundary issues

The functional unit to which the input and output process data were normalised was one hectare of semi-natural grassland, as an area related unit allows the comparison of management systems with different output products. Furthermore, difficulties in the allocation of input flows on several output products can be avoided.

Inputs and outputs were taken into account along the entire process chain, including raw material acquisition, production and disposal following the cradle-to-grave principle used in LCA. Environmental impacts resulting from the supply of infrastructure such as buildings, machinery, and roads, were disregarded, as they contribute less than 10% to the total energy input over a time span of 20 years (Bühle et al., 2011c). Thus, only energy and material flows resulting from continuous operation were taken into consideration.

2.4. Reference system and carbon soil dynamics

Assessment of the energy recovery systems was conducted, assuming that fossil-based technologies with the same function of supply are replaced. Data for fossil systems related to the average of heat (50% natural gas, 50% fuel oil) and electricity production (43% coal, 21% nuclear power, 15% natural gas) under German conditions and were taken from GEMIS database (Anonymous, 2011). Comprehensive LCA of agricultural systems has to consider not only the replaced function, but also the displaced function of previous land use. Considering the increasing abandonment of semi-natural grasslands in Europe, it was assumed that the energy production from semi-natural grassland does not imply a displacement of food or energy crop systems. Thus, no reference system for displaced land use was considered. Only emissions of nitrous oxide from the soil were credited to the scenarios, as they occur in any case independent of the grassland use.

In general, soil carbon dynamics must be taken into account for LCA studies, particularly in the case of land use and management changes, due to their impact on greenhouse gas balances by C sequestration or release from soils. In the present study, the carbon level in the extensively managed grassland soils was assumed to be in equilibrium, without net sequestration or release of CO_2, as the previous management of regular cutting is consistent with the management considered in the LCA. C sequestration from organic residues, which are redirected to intensively managed grasslands in this study, was disregarded as well, as there are major uncertainties in terms of humus accumulation (Soussana et al., 2010). Studies report constant levels (Smith et al., 2001) as well as