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Life cycle assessment of different bioenergy production systems including perennial and annual crops

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ABSTRACT

Energy crops are expected to greatly develop in a very short-term bringing to significant social and environmental benefits. Nevertheless, a significant number of studies report from very positive to negative environmental implications from growing and processing energy crops, thus great uncertainty still remains on this argument. The present study focused on the cradle-to-grave impact assessments of alternative scenarios including annual and perennial energy crops for electricity/heat or first and second generation transport fuels, giving special emphasis to agricultural practices which are frequently surprisingly neglected in Life Cycle Assessment studies despite a not secondary relevance on final outcomes. The results show that cradle-to-farm gate impacts, i.e. including the upstream processes, may account for up to 95% of total impacts, with dominant effects on marine water ecotoxicity. Therefore, by increasing the sustainability of crop management through minimizing agronomic inputs, or with a complementary use of crop resides, can be expected to significantly improve the overall sustainability of bioenergy chains, as well as the competitiveness against fossil counterparts. Once again, perennial crops resulted in substantially higher environmental benefits than annual crops. It is shown that significant amount of emitted CO_2 can be avoided through converting arable lands into perennial grasslands. Besides, due to lack of certain data, soil carbon storage was not included in the calculations, while N_2O emission was considered as omitted variable bias (1% of N-fertilization). Therefore, especially for perennial grasses, CO_2 savings were reasonably higher that those estimated in the present study. For first generation biodiesel, sunflower showed a lower energy-based impacts than rapeseed, while wheat should be preferred over maize for first generation bioethanol given its lower land-based impacts. For second generation biofuels and thermo-chemical energy, switchgrass provided the highest environmental benefits. With regard to bioenergy systems, first generation biodiesel was less impacting than first generation bioethanol; bioelectricity was less impacting than first generation biofuels and second generation bioethanol by thermo-chemical hydrolysis, but highly impacting than Biomass-to-Liquid biodiesel and second generation bioethanol through enzymatic hydrolysis.

1. Introduction

Biofuels are required to fulfil the environmental aims to be eligible for financial support [1–3]. Therefore, significant and certain environmental benefits from fossil fuels displacement by biofuels is *sine qua non* for their public acceptance. Most studies indicate that this can be generally true [4–6], and the use of biofuels will bring to substantial reductions of GHG

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emissions, air pollution, acidification, eutrophication, ozone depletion and human health damages [7–9]. However, the extent of these benefits will depend on species, crop management, land allocation, scale level and environmental characteristics [10,11]. That biofuels bring to certain benefits is not universally accepted since some studies report negative effects of biofuels in comparison to their fossil counterparts [12–16] or alternative renewable energies [17]. The reason of these conflicting results is the uncertainty and variability of Life Cycle Assessment (LCA) procedures [18], that is the inherent variation in the real world (variability), and lack of data, inaccurate measurements, model assumptions etc. (uncertainty). LCA outcomes may in fact radically change with agricultural practices (e.g. fertilizers, pesticides etc.), local conditions, crop yields and the direct and indirect land use change effects [19]. In a recent study, for example, Fargione et al. [20] argued that the conversion of native ecosystems, such as peatlands and savannas, to biofuel crops would result in large carbon debts for several decades, especially if biofuels derive from annual crops; however, if the energy crops are perennial grasses grown on degraded and abandoned lands they can offer immediate advantages in term of GHG emission savings. Therefore, punctual and accurate assessments on the real benefits of biofuels, especially of some less known impact categories, such as human health and ecosystem quality [21,22], should be urgently provided in order to understand the future environmental role of energy crops [23] that are expected to cover million hectares in Europe in a very short-term [2].

The main objective of this study was, therefore, to estimate the cradle-to-grave environmental effects, i.e. from manufacture (cradle) to disposal (grave), caused by alternative biofuel chains, and to characterize their impacts into major categories (e.g. eutrophication, marine water ecotoxicity, human health etc.). The impacts were calculated according to LCA methodology [24,25], the likely broadest used tool to estimate the environmental implications generated by production processes, services and technologies [26]. The overall impact of biofuels are obtained by gathering impacts deriving by a set of processes, starting from seedbed preparation to harvest and conversion of feedstock into energy or biofuels.

In biofuels LCAs an important source of uncertainty is the low accuracy in the definition of the impacts resulting from different cultivation practices (e.g. ploughing depth, carbon stored by belowground biomass etc.). Commonly, the LCA databases are little detailed on agricultural practices that instead may significantly change the LCA outcomes [9,11,24,27,28]. Therefore, in the present study we used more accurate data on field practices, that were either directly measured or collected from literature and interviews.

According to whether the feedstock is processed for electricity, heat, transport fuels or other mid compounds (e.g. syngas or hydrogen) will radically change the environmental loads of the bioenergy chain. A crop potentially suited to alternative energy purposes (e.g. electricity or bioethanol) should be therefore assessed under different scenarios thus to identify the most sustainable energy use for each crop. For example, switchgrass may be processed for solid or liquid biomass to produce electricity/heat or 2nd generation transport fuels through the hydrolysis of cellulose into soluble sugars followed by fermentation. Again, cynara (or cardoon) can be combusted as whole plant to produce electricity or separated out seeds for biodiesel production; fibre sorghum can be used to extract cellulose for 2nd generation bioethanol or combusted for electricity. In the present study, we considered several annual and perennial energy crops each having potential alternative energy uses in order to identify the likely most sustainable utilization on hectare and energy basis. Briefly, land-based impact represents the net environmental benefit given by energy crops, while the energy-based impact is mostly useful for debottlenecking purposes as it accounts for the process efficiency. Therefore, land- and energy-based impacts have different meanings and can be not necessarily related. The sensitivity analysis was also carried out to understand to what extent the use of crop residues can reduce the total environmental impacts of a bioenergy production system.

2. Materials and methods

2.1. LCA methodology

The environmental impacts of four perennial and five annual crops were estimated: miscanthus (*Miscanthus × giganteus* Greef & Deuter), giant reed (*Arundo donax* L.), switchgrass (*Panicum virgatum* L.), cynara (*Cynara cardunculus* L.), fibre sorghum (*Sorghum bicolor* L.), maize (*Zea mais* L.), wheat (*Triticum* spp. L.), rapeseed (*Brassica napus* L.) and sunflower (*Helianthus annuus* L.), the last five being annual crops.

The environmental impacts were assessed according to standard LCA procedures, as given by the International Organization Standardization [26], and then implemented by SimaPro LCA software [29]. Criteria adopted for LCA calculation (scope definition, inventory, LCIA etc.) were already described in detail elsewhere [30]. CML2 baseline 2000 [31] and Eco-indicator 99 [32] were used as impact assessment methods.

Cradle-to-grave impacts of each scenario were compared on land- (hectare) and energy- (Joule) basis (Fig. 1). Hectare-based impact (EI/ha) accounts for the magnitude of impacts at different scale levels (net environmental gain), while energy-based impact (EI/J) represents the process environmental efficiency. The land-based assessments allow to compare products with different purposes (e.g. food crops and energy crops), while the energy-based impacts are used for comparing only the energy crops.

2.2. Impact categories

Impact categories (Table 1) were already described in a previous article [30]. In short, the impact categories (IC_i) were calculated as following:

$$IC_i = \sum_j E_j \cdot CF_{i,j}$$

E_j is the emission release (or consumption) of the generic resource j; $CF_{i,j}$ is the characterization factor, i.e. the relative contribution of j compound to i impact category [33]; for