LIFE CYCLE ASSESSMENT OF MANAGEMENT STRATEGIES FOR RESIDUAL GRASS

Version 1.0

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1 PREFACE

Between 2007 and 2013, more than 400 European projects have been funded through the Intelligent Energy Europe Programme in the broad endeavour to promote energy efficiency and renewables. Grass to Green Gas (GR3) is one of these projects. The geographical scope of the GR3 project is the Veneto region (Italy), Flanders (Belgium), Saarland (Germany), Great Lisbon (Portugal) and Denmark (overall). The overall aim of GR3 is to promote the use of grass and other herbaceous residues as a resource for biogas production in the above-metioned regions (more information about the GR3 project are available on the project website: www.grassgreenresource.eu).

Yet, one question remains to be answered. Is it environmentally efficient to do so? And if so, how and under which framework conditions? The present report is an integral part of the GR3 project and is meant to answer these key questions. Besides biogas, other uses (or strategies) for residual grass such as composting and bio-refining are also investigated. A sister report (CBA report; available on the project website) endeavours to supply answers on which management strategies for residual grass are economically-efficient.

This report (version 1) presents the key LCA scenarios and results only. The calculations are detailed in an accompanying appendix to be available on the project website.

The report was authored and edited by Lorie Hamelin (University of Southern Denmark) with contributions and key input from all GR3 partners.

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2 INTRODUCTION

Recovery of biogas from organic residues is an acknowledged cost-effective mitigation technology for greenhouse gases [1]. In the perspective of a fully renewable energy system, biogas also offers the possibility to be storable in the gas network, which provides flexibility for buffering the fluctuant energy supply from intermittent sources like wind and sun, as well as a fuel for transport.

A recent analysis [2] of the national renewable energy action plans (NREAP) made by the European Member States in the framework of the renewable energy directive (RED) [3] highlights that European Member States have provided ambitious biogas targets to meet their renewable energy obligations. Based on this, important increases in biogas can be foreseen in the short-to-medium term horizon. In Denmark, for example, a target has been launched to achieve 50% use of manure for biogas by 2020 [4] as compared to the present use of only 5-7% [5]. Yet, this requires a feedstock input. Not all countries dispose of animal manure resources, and when manure is available, it is a common practice for biogas plants to co-digest it with C-rich substrates, in order to ensure a biogas production safeguarding the economic sustainability of the production [1,6,7]. As the short-comings of biogas strategies relying on energy crops gained increased attention in the recent years [e.g. 1], there is now a need to find new organic substrates for biogas.

To this end, grass residues, such as those from roadsides or nature landscapes, could represent a new opportunity. Unlike agricultural residues which have been widely studied [e.g. 1,8–10], grass residues received little attention, remaining generally underutilized throughout Europe.

However, the use of residual grass biomass for the production of energy or other useful products does not necessary involve an environmental improvement. These residues, if not used for e.g. biogas, would have been used for other applications (this includes the “no-harvest” situation where the grass is left to decay on-site). As highlighted in recent studies [e.g. 1,9,10], the environmental performance of management strategies for residual biomass is closely dependant on the alternate use for these, also refered to as the “lost opportunity”.

The aim of this study is to assess the environmental consequences related to diverse uses of grass residues in Europe. It will answer to main questions : i) is the overall environmental performance increased when grass residues are used for biogas, in comparison to their current use; and ii) what are the differences in environmental performance between different strategies to manage residual grass, in comparison to it’s current management?

Five main scenarios are considered: anaerobic digestion, composting, animal feeding, integrated generation of solid fuel and biogas and a green biorefinery concept (production of protein and energy).

It is important to mention that the focus of the study (and of the overall GR3 project) is residual grass. Therefore, any grass that is purposely cultivated for bioenergy/biorefining use is not included within the scope of this study.

3 METHODOLOGY

3.1 ENVIRONMENTAL ASSESSMENT METHODOLOGY

This section intends to give a short introduction to the life cycle assessment (LCA) methodology in general, as this is the environmental assessment methodology applied in this study. In brief, LCA is a standardized comparative environmental assessment methodology [11,12] which consists of assessing and comparing the environmental impacts of selected product/service alternatives from “cradle-to-grave”, i.e. from raw materials extraction, through processing and product manufacturing, encompassing product use and maintenance and finally including ultimate disposal of the product at the end of its lifetime. A state-of-the-art LCA thus includes all significant flows from and to the environment involved in the studied system[1], aggregates them over all life cycle stages and subsequently expresses them per unit of function delivered by the system in question, which in LCA is referred to as the “functional unit”. This latter stage ensures that the comparison is based on the delivery of the same service in all systems compared. These aggregated substance flows are then related to an impact category and the contribution from each substance to these impact categories is quantified through a procedure known as life cycle impact assessment (LCIA). This procedure, divided in 4 main steps, is extensively described in [13–15]. It allows, for a given impact category (e.g. global warming), to express the aggregated flows as an indicator, or reference substance, (e.g. kg CO_2 eq.) per functional unit, through the use of equivalence factors (e.g. 298 kg N_2O per kg CO_2 eq.). Additional details on the general principles of the LCA methodology can be found in [16–18].

There is a broad agreement within the scientific community that LCA is one of the most appropriate tools for the evaluation of the environmental burdens associated with biofuels and overall bioenergy production [19–21], or with products in general [17]. However, LCA has also been criticized, among others for the discrepancy between the LCA results obtained from different studies assessing similar systems (e.g. [22,23]) and for being a rather static methodology, not allowing to capture important dynamic effects such as competition and substitution between different uses for the products involved in the studied system (e.g.[19]).

It is the postulate of the author that these critics can be overcome through the application of the so-called consequential LCA methodology (c-LCA), a method representing the convergence of LCA and economic modeling methods [24]. There are two essential differences between consequential and “traditional” LCAs (referred to as attributional LCAs, or a-LCA). The first is the way the two approaches deal with processes having multiple product outputs. Attributional LCAs aim to ascribe all impacts from the studied system to a single ‘main product’ output from the system by some way of partitioning the various flows (emissions, resource extractions, etc.) involved in the system between the studied main product and its co-products. Consequential LCAs instead expand the system and aim to include the alternative products on the market displaced by the co-products. The other major difference is a logical implication of applying system expansion, and regards the type of data included in the LCA model. While attributional LCA uses “average data” (e.g. an

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[1] The compilation of these flows is referred to as the Life Cycle Inventory (LCI).

average of all electricity sources used in a given national electricity mix), consequential LCA includes "marginal data" only, i.e. data representing the processes and/or suppliers that are responding to changes in demand by corresponding changes in supply. Additional information on the implications of these LCA methodologies, including illustrative examples, is available in [25] as well as in [26], among others.

In the present study, the consequential LCA methodology was applied. The goal of a consequential LCA is to study the consequences of the decisions it aims to support (in the present case, these relate to the management of grass residues). From this point forward, unless otherwise specified, the acronym "LCA" will be used in reference to the consequential LCA methodology.

3.2 GOAL, SCOPE AND FUNCTIONAL UNIT

This study endeavours to provide quantitative answers to the following question: "What are the environmental benefits and drawbacks of introducing a given management strategy for residual grass, in comparison to today's situation?"

This study considers a short-term time scope (period 2015-2030). The geographical scope is Europe, i.e. the the inventory data for the grass composition and for the involved technologies were specific to the European context. Any systems affected outside Europe, for example fertilizers production, are obviously also included, in accordance with consequential LCA principles.

All input and output flows were related to a functional unit being the management of one tonne of residual grass (meadow grass from natural areas; section 4.1).

3.3 IMPACT ASSESSMENT

The life cycle impact assessment was carried out according to the EDIP 2003 methodology [27] for the impact categories global warming (100 years horizon), acidification and aquatic eutrophication (distinguishing between nitrogen and phosphorus being the limiting nutrient for growth). One adjustment from [27] is that the global warming potential factors were updated to those recently proposed in the latest assessment report 5 (AR5) of the IPCC [28], i.e. 34 kg CO_2 eq. kg^{-1} CH_4 and 298 kg CO_2 eq. kg^{-1} N_2O (factors with inclusion of climate-carbon feedback).

3.4 DATA

Background (or generic) LCA data were based on the Ecoinvent v.3 database, and the LCA was facilitated with the LCA software SimaPro 8. Foreground (or system-specific) LCA data essentially included data for the substrates composition, biogas production and overall energy conversion technologies. Impacts associated with capital goods in the foreground processes were excluded due to lack of data.

3.5 ANAEROBIC DIGESTION

The biogas production considered in this study is based on a two-steps anaerobic digestion consisting of a completely stirred main digester and a post-digester from which ca. 10% additional CH_4 emissions are captured. It is assumed that the production is operated under mesophilic conditions, and that the biogas produced is constituted of 65% CH_4 and 35% CO_2, with a density of 1.158 kg Nm^{-3} biogas [7] and a LHV of 22.88 MJ Nm^{-3} biogas. Fugitive losses of 1% of the CH_4 produced were assumed, considering the establishment of best available technologies. As shown in for example [10] or [1], higher fugitive losses (5% in the former, 10% in the latter) do hamper the greenhouse gas balance of biogas strategies, due to the important global warming potential of methane. Yet, as highlighted in [1], such high fugitive losses may not be so realistic in a context where new (state-of-the-art) plants are established, and where plants seek to be financially viable.

The biogas is considered to be burned in a biogas engine with efficiencies of 46% for heat and 40% for electricity [7]. The emissions data considered for the CHP process are from [29,30] and it is assumed that only 90% of the net heat produced can substitute marginal heat, reflecting the losses occurring in periods with low heat demand [1]. To reflect another extreme (e.g. the conditions of Southern Europe in warm years), a sensitivity analysis assuming that only 20% of the net heat produced can substitute marginal heat was performed. Internal electricity consumption corresponding to 5% of the net electricity production [7,31] was assumed. Internal heat consumption was calculated considering that the mixture is heated from 8°C to 37°C. This is considered to reflect well the conditions for Denmark, Belgium and Germany, but may slightly overestimate the internal heat used for Italy and Portugal cases. The heat requirement was calculated considering a specific heat of 3.00 kJ kg^{-1} $°C^{-1}$ for the DM share of the input mixture, and of 4.20 kJ kg^{-1} $°C^{-1}$ for the water, based on [7].

As described in section 3, some scenarios involve co-digestion. In this case, the mixture was calculated in order to get a mixture reaching a dry matter (DM) content of 10% after the first digestion step, and a carbon to nitrogen (C/N) ratio limited to 25. From the anaerobic digestion step, two outputs are produced: the digestate and the biogas. The biogas is assumed to be used for combined heat and power (CHP), as above-described. In this study, the marginal electricity source displaced by the biogas was assumed to be from coal-fired power plants, and the marginal heat from natural gas based domestic boilers. The other output from the anaerobic digestion process, namely the digestate, was assumed to be stored in a concrete tank covered with a straw floating layer. When appropriate, this digestate can be applied on agricultural fields as an organic fertilizer, thereby displacing mineral nitrogen (N), phosphorus (P) and potassium (K) fertilizers, considered to be calcium ammonium nitrate, diammonium phosphate and potassium chloride, respectively (marginal fertilizers). Marginal fertilizers, like for the marginal heat and electricity sources, are, in consequential LCA, those affected by a change in demand, and were identified as described in [25]. The algorithms used to calculate the emission losses of C-compounds (CO_2, CH_4), N-compounds (NH_3, N_2O, NO_x, N_2, NO_3) and P losses to water during the storage and application of the digestate(s) are as described in [1].

Changes in soil C occurring as a result of applying the digestate on land were estimated with the dynamic soil C model C-TOOL [32–34].

3.6 GRASS SILAGE

It is considered that the fresh harvested grass (grass “ex-harvest”) is stored prior to its use by the biogas plants. The storage method selected is ensiling, and the duration of silage may vary, and thus the grass may see an alteration in composition. The changes in composition are calculated for a silage duration of 2 months, considered to be a plausible storage time. DM losses of 1.8% were considered during the silage process. Considering the algorithm presented in [35] for the degradation of organic matter (for a complete conversion), all the DM losses occurring during silage were translated to CO_2 and NH_3 emissions, using the same procedure described in [1].

4 SCENARIOS

4.1 REFERENCE GRASS MANAGEMENT

The LCA focuses on grass from natural areas (nature conservancies, permanent grassland from extensive areas, etc.). Fresh meadow grass was selected as a representative to this end.

It is here considered that the default situation is that this meadow grass is left un-harvested, where it simply decays on-site. Considering an annualization period of 100 years for soil C changes, it was assumed that 100% of the carbon in the decaying grass ends up emitted to the atmosphere.

4.2 MAIN SCENARIOS

The scenarios assessed are described below. The details on the substrates composition and biochemical methane potential (BMP) are presented in section 4.3. The process flow diagrams illustrating the system boundary considered for each scenario are presented in Figures 1-5 (section 4.4).

4.2.1 SCENARIO 1 - BIOGAS

The harvested grass is co-digested with 30% pig slurry (based on the parameters described above to model co-digestion); the digestate is stored and applied on farmland as a source of fertilizer and the biogas is used for combined heat and power (CHP) production, thereby avoiding marginal fertilizers, heat and electricity to be produced.

Sensitivity analyses for scenario 1:

(a) with extrusion pre-treatment for the grass (in which case the mixture becomes 50% slurry, 50% grass). This scenario essentially reflects the effect of a higher BMP for grass. Extrusion was considered to increase the grass biodegradability to 61% (which in this case implies a CH_4 yield increase of 35%), and to consume 14.5 kWh per t of fed grass, based on the average results obtained by [36].

(b) with extrusion, but only 1% slurry input (reflecting mono-digestion; a minimal slurry input was nevertheless considered necessary to ensure a stable digestion process and avoid the addition of micro-nutrients).

If not co-digested with the grass, it is considered that pig slurry would have otherwise been managed conventionally, i.e. stored and applied on land without any additional treatment, as described in [7].

4.2.2 SCENARIO 2 - COMPOSTING

The harvested grass is composted along with 15% wood chips in order to obtain a quality compost, subsequently applied on household gardens. This mixture was selected in order to ensure a C/N ratio below 25 for the final compost, and a final DM in the range of 40 – 60% [37]. The emissions occuring during the composting process, as well as during the storage and application of the compost were modeled with the algorithms described in [1].

This compost does not replace mineral fertilizers; it was considered that without this (often free) compost, a lower yield for home gardens would simply be accepted. If not used for compost, the wood chips would have been used for CHP in small-to-medium scale biomass CHP plants, thus avoiding marginal heat and electricity production. Efficiencies of 27% and 63% for electricity and heat, respectively, are considered for such biomass combustion CHP plants, based on [38].

4.2.3 SCENARIO 3 – ANIMAL FEEDING

The harvested grass is used as animal feed, based on its protein and carbohydrate content. This involves that the grass replaces part of the protein and carbohydrate crops needed for animal feed. This scenario includes the indirect land use changes avoided as grass substitutes for wheat (marginal carbohydrate crop) and soy meal (marginal protein crop). The impacts due to land use changes on greenhouse gases are calculated as described in section 5.

4.2.4 SCENARIO 4 – INTEGRATED GENERATION OF SOLID FUEL AND BIOGAS (IFBB)

The harvested grass is here washed, stirred, heated and finally pressed where it is separated into two fractions: a liquid used for biogas production (co-digestion with straw; wheat straw is used as a representative) and a solid from which solid fuel pellets are produced (85% DM), as further described in [39]. Both the biogas and pellets are used for CHP. If not co-digested with the liquid fraction from the IFBB process, it is considered that straw would have been left on land and ploughed down. This was modeled as described in [1].

The emissions from the combustion of the solid fuel pellets were modeled based on the data from [29] (data for straw), except for the CO_2, which was estimated as the difference between the total C in the solid fuel and the CH_4-C loss (taken from [29]). The electricity and heat efficiencies considered for the biomass combustion plant are as for wood chips in scenario 2 (27% and 63%, respectively).

4.2.5 SCENARIO 5 – GREEN BIOREFINERY

The harvested grass is pressed, but the solid is here used for co-digestion with pig slurry, while the liquid is further processed (steam coagulation and decantation) to produce a protein-rich cake used for animal feed.

The portion of water, DM, VS and C ending up in the press cake (solid fraction) and in the press juice (liquid fraction) after the pressing of the fresh grass were modeled based on [40].

As in scenario 3, indirect land use changes are included in this scenario, to reflect the feedstock avoided through the inclusion of the protein-rich cake in animal feed. The same modeling principles were applied.

4.3 SUBSTRATE COMPOSITION AND BIOCHEMICAL METHANE POTENTIAL

The key parameters of the biochemical composition of the substrates involved in this study as well as their biochemical methane potential is presented in Table 1.

TABLE 1. SUBSTRATE COMPOSITION AND BMP

		Fresh meadow grass	Pig slurry (ex-housing)	Straw	Wood chips
DM	kg t^{-1} ww	180	69	850	850
N	kg t^{-1} ww	1.6	5.3	4.5	1.7
P	kg t^{-1} ww	0.6	1.2	0.8	1.4
K	kg t^{-1} ww	5.3	2.9	13	13
C	kg t^{-1} ww	72	34	383	420
VS	kg t^{-1} ww	160	55	811	680
BMP	Nm^3 CH_4 t^{-1} VS	302 *(410 when extruded)*	320	195	-
Scenarios	-	1-2-3-4-5	1-5	4	2
Reference	-	[36,41,42]	[1]	[1]	[1,43]

4.4 PROCESS FLOW DIAGRAMS

The system boundary of all assessed scenarios are illustrated below as process flow diagrams (Figures 1-5).

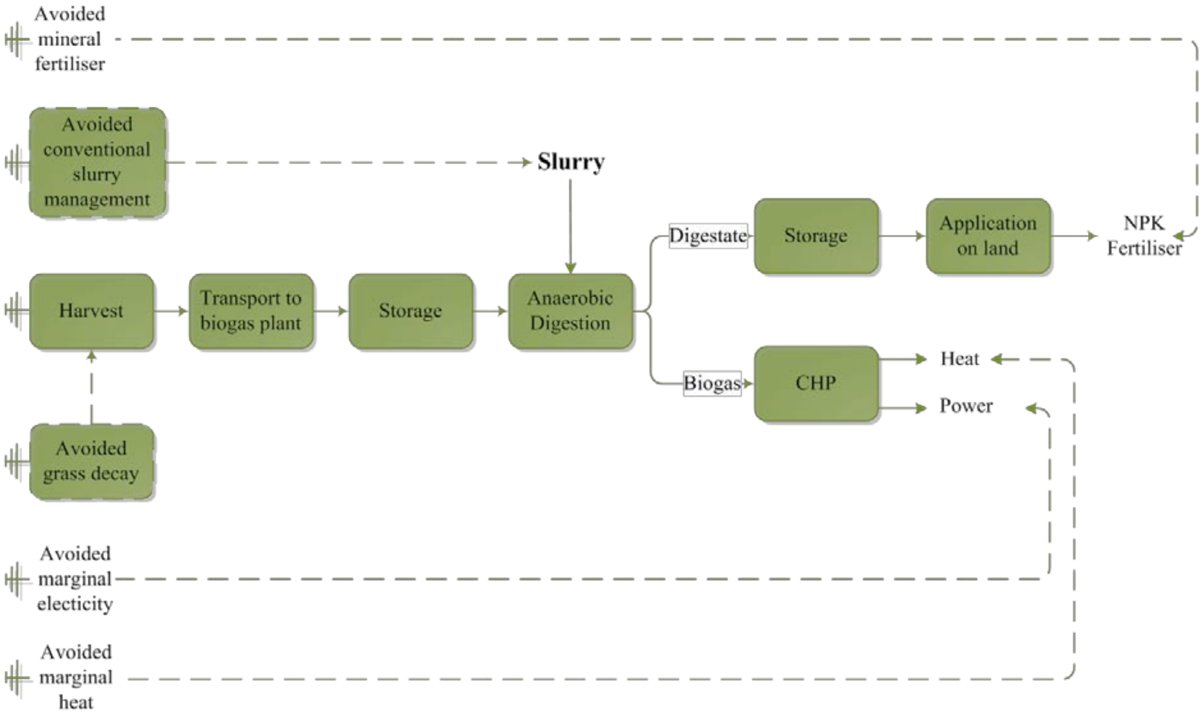

Figure 1: ***Process flow diagram for scenario 1 – biogas. The baseline case is illustrated (co-digestion + no grass extrusion). Dotted lines indicate avoided flows.***

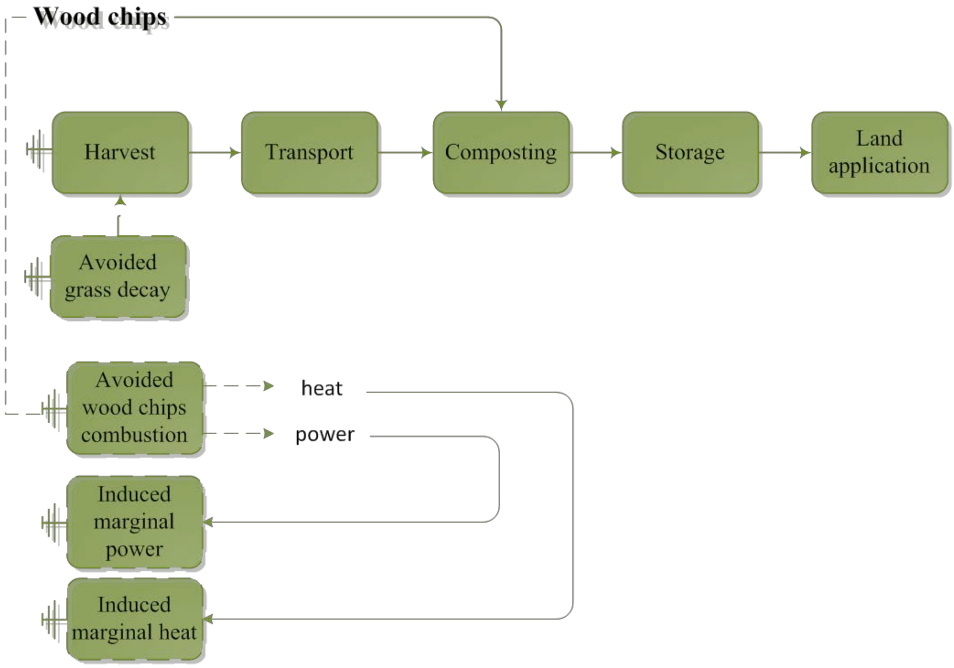

Figure 2: Process flow diagram for scenario 2 – composting. Dotted lines indicate avoided flows.

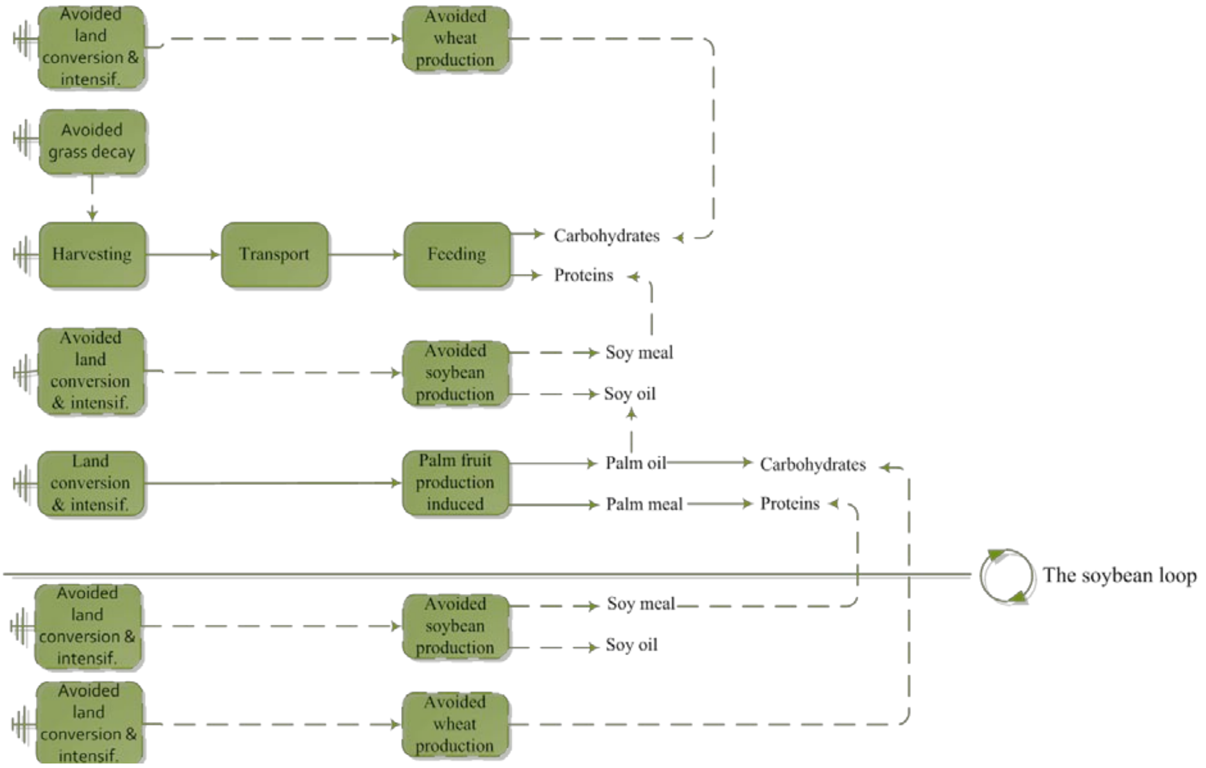

Figure 3: Process flow diagram for scenario 3 – animal feeding. Dotted lines indicate avoided flows. The system boundary considered here excludes, for simplicity, the protein share of the palm

fruit meal, which would involve a continuous soybean loop. It is therefore assumed that considering this would yield no further information that is significant for decision making. For more details on the soybean loop illustrated herein, see [44]**.**

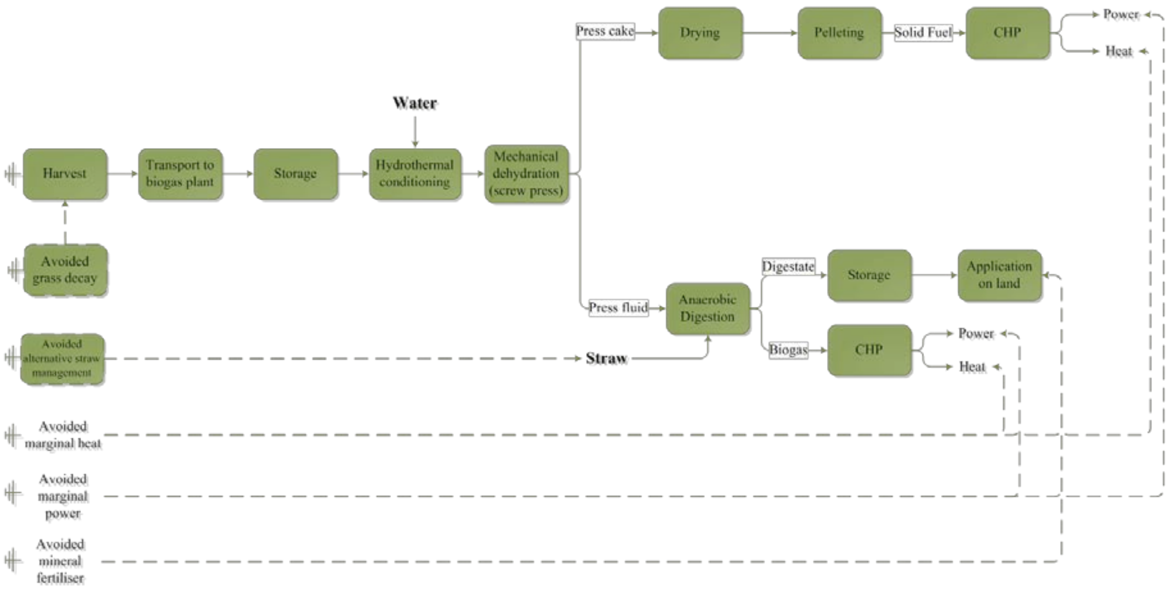

Figure 4: Process flow diagram for scenario 4 – IFBB. Dotted lines indicate avoided flows.

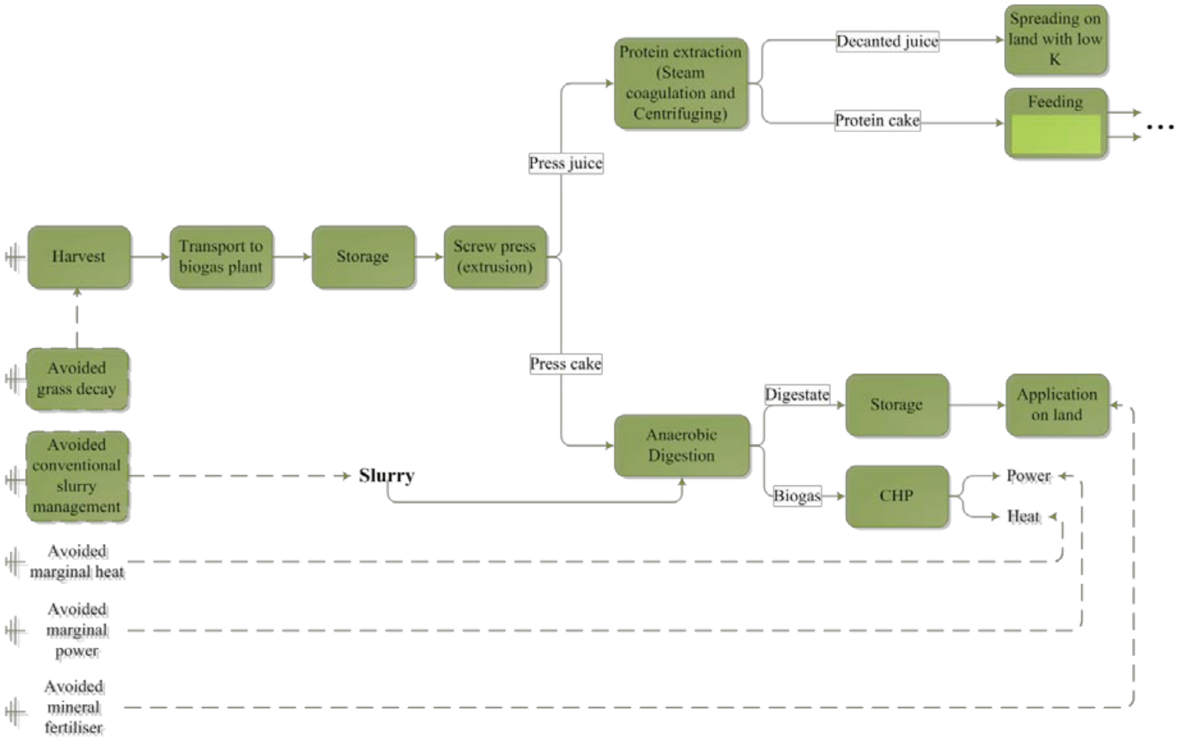

Figure 5: Process flow diagram for scenario 5 – green biorefinery. Dotted lines indicate avoided flows. The dots (...) indicate that the processes following this box are exactly as those following the box "feeding" in scenario 3.

5 MODELLING OF INDIRECT LAND USE CHANGES

Modelling the land use changes avoided by the use of grass residues for animal feeding (scenarios 3 and 5) involve three main steps:

1) Determining the amount of marginal crop whose cultivation is avoided;
2) Determine the iLUC response, in terms of expansion and intensification, related to (1)
3) Quantify the release of substance flows in relation with (2).

Step 1 was address on the basis of the nutritional value of grass (carbohydrates representing 94% of the VS, and protein 6%). It is considered that the carbohydrates need is fulfilled by wheat, and the protein need by soybean (marginal carbohydrate and protein source, respectively). Based on this, it was calculated that:

- Wheat avoided, due to carbohydrates in grass: 213 kg (scenario 3)
- Soybean avoided, due to protein in grass: 25 kg (scenario 3); 8 kg (scenario 5)
- Palm fruit induced, due to soy oil avoided (see process flow diagrams): 18 kg; (scenario 3); 6 kg (scenario 5)
- Wheat avoided, due to palm meal produced: 0.5 kg (scenario 3); 0.2 kg (scenario 5)

The deterministic developed in [9] was used to model the release of C-compounds (CO_2) and N compounds (N_2O, NH_3, NO_3, NO_x) due to the land use changes (steps 2 and 3). This model, based on the latest deforestation data available [45], takes full account of both expansion and intensification responses. Overall, this model determines that the GHGs from iLUC impacts correspond to 4.1 t CO_2 eq. ha^{-1} demanded y^{-1}.

6 RESULTS AND DISCUSSION

Except composting (660 kg CO_2 eq. t^{-1} grass), all scenarios led to an improvement of the global warming potential (GWP_{100}), in comparison to the no-harvest situation (Fig. 6). Compared to (extruded) grass mono-digestion (-130 kg CO_2 eq. t^{-1} grass; scenario 1b), the IFBB system allowed an additional 50% GWP_{100} reduction, while the biorefinery led to twice the savings, and the animal feeding scenario to more than four times the savings of mono-digestion. For the latter two, it reflects the benefits of using grass for protein substitution (here soybean meal), and thus of reducing the pressure on land in sensitive ecosystems.

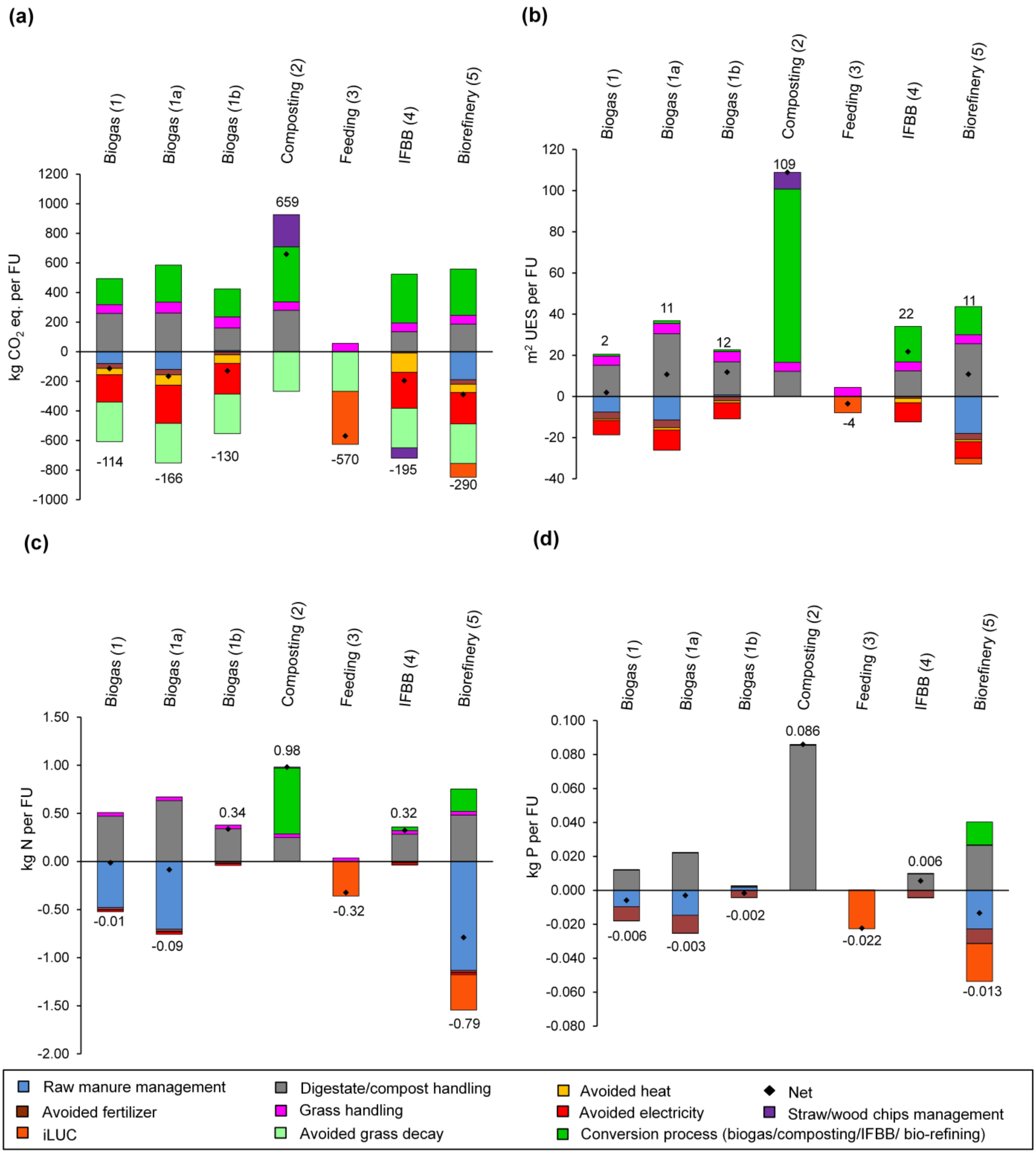

Figure 6: Breakdown of the LCA results for all impact categories (a) global warming (100 y); (b) acidification; (c) aquatic-N eutrophication; (d) aquatic-P eutrophication. Expressed per functional unit, i.e. 1 tonne of freshly harvested grass

For all impact categories, composting led to increased environmental impacts, in comparison to the no-harvest situation (Figure 6). This reflects the important loss of nitrogen and carbon during the composting process. Except composting, losses of nitrogen and phosphorus to freshwater were negligible for all scenarios. Acidification was increased for all scenarios but feeding, reflecting the production of ammonia during digestate handling. This, however, could be minimized through careful pH control.

Figure 6a highlights the benefits, in terms of GWP_{100}, of avoiding grass to decay on-site, and such benefits also applied for all other impact categories. An additional benefit of harvesting the grass, though not reflected in the LCA, is the enhanced biodiversity; by cutting and harvesting the grass, a new opportunity is created for other plant species to prosper. Figure 6 further reflects, as emphasized in previous studies (e.g.[1]), the tremendous environmental benefits of digesting manure instead of managing it conventionally; the scenarios triggering more manure to be digested thus lead to additional environmental benefits. Similarly, the scenarios triggering more electricity production (1a, 4) led to important environmental benefits (Fig. 6).

It is important to understand that the energy-related benefits shown in Fig.6 are directly related to the source of marginal energy avoided by the biogas or pellets produced. In a future renewable energy context with a high share of fluctuating power (wind), the avoided energy would have GWP credits close to zero. However, biogas, being storable, would not displace continuous but flexible power [46], when not used for transport. As shown in [46], the marginal source of flexible power may come from biomass with potentially high environmental impacts. In such setting, producing pellets from the grass (scenario 4) appears less advantageous in comparison to biogas production, since these can only be used for continuous CHP production.

One important limitation of this study is that it was considered that 100% of the carbohydrate and protein value of the grass could substitute for marginal carbohydrate (wheat) and protein crop (soy), respectively. In reality, it is not the crude protein content that matters the most for animal feeding, but the quality of the protein in terms of amino acids. Further, the overall quality of the grass (contamination, etc.) may not meet the standards required to accept it 100% as a direct feed source (as assumed in scenario 3), so the benefits of scenario 3 may be slightly overestimated. Through this is not expected to change the overall ranking between scenarios, the model would benefit from refinements on these aspects.

Finally, it may be argued that the compost would avoid mineral fertilizers or even peat amendements as considered in some studies [47,48]. The latter would likely cancel the global warming impacts of the composting scenarios due to the important global warming benefits of avoiding peat extraction. Yet, the possibility of home garden owners using peat as a default was here judged pretty unlikely. It was considered more plausible that without free (or cheap) grass-based compost, home garden owners would simply accept a lower yield and would not apply anything.

7 CONCLUSION

Except composting, all management scenarios of residual grass led to increased environmental benefits in comparison to today's no-harvest situation, for all impact categories assessed. Alternatives allowing to recover a maximum of protein (animal feeding, green biorefinery) generated the greatest benefits, essentially due to the avoided land use changes this creates. The green biorefinery concept, allowing to simultaneously recover substantial energy, protein and fertilizers, was shown as a promising avenue for managing residual grass on an environmentally-efficient manner.

8 ACKNOWLEDGEMENT

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