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Environmental hot spot analysis in agricultural life-cycle assessments – three case studies

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Abstract

Present-day agricultural technology is facing the challenge of limiting the environmental impacts of agricultural production – such as greenhouse gas emissions and demand for additional land – while meeting growing demands for agricultural products. Using the well-established method of life-cycle assessment (LCA), potential environmental impacts of agricultural production chains can be quantified and analyzed. This study presents three case studies of how the method can pinpoint environmental hot spots at different levels of agricultural production systems. The first case study centers on the tractor as the key source of transportation and traction in modern agriculture. A common Austrian tractor model was investigated over its life-cycle, using primary data from a manufacturer and measured load profiles for field work. In all but one of the impact categories studied, potential impacts were dominated by the operation phase of the tractor's life-cycle (mainly due to diesel fuel consumption), with 84.4-99.6% of total impacts. The production phase (raw materials and final assembly) caused between 0.4% and 12.1% of impacts, while disposal of the tractor was below 1.9% in all impact categories. The second case study shifts the focus to an entire production chain for a common biogas feedstock, maize silage. System boundaries incorporate the effect of auxiliary materials such as fertilizer and pesticides manufacturing and application. The operation of machinery in the silage production chain was found to be critical to its environmental impact. For the climate change indicator GWP100 (global warming potential, 100-year reference period), emissions from tractor operation accounted for 15 g CO_2-eq per kg silage (64% of total GWP100), followed by field emissions during fertilizer (biogas digestate) application with 6 g CO_2-eq per kg silage (24% of total GWP100). At a larger system scale that includes a silage-fed biogas plant with electricity generated by a biogas engine, silage cultivation operations are no longer the largest contributor; the most important contributor (49.8%) is methane slip from the exhaust of the biogas engine. In the third case study, the biogas plant model is incorporated into an even larger system, where the existing waste management and energy system in an Alpine municipality of Western Austria is expanded to include a hypothetical system that uses mainly hay from currently unused alpine grassland in a local biogas plant. Here, the relative environmental impacts depend strongly on the fossil fuels that are assumed to be displaced by the local biogas plant; methane slip emissions from the exhaust dominate the impact of the hypothetical local biogas scenario. Taken together, the case studies demonstrate the potential and limitations of LCA as a technique to support decisions of agricultural stakeholders at a variety of scales. Choosing the proper system scale is key to a successful application of this method.

Keywords: biogas, hotspot analysis, life cycle assessment, maize silage, tractor

Introduction

Present-day agricultural technology is facing the challenge of limiting the environmental impacts of agricultural production while meeting growing demands for agricultural products (see for example Valin et al., 2013). However, a wide variety of stakeholders is active in agriculture and agroindustry, with varying options and challenges to mitigate environmental impacts in their sphere of influence. As a well-established decision support tool, the method of life-cycle assessment is a quantitative way to estimate the potential environmental impacts of products and services in general, and of agricultural process chains and products in particular (Caffrey and Veal, 2013). This can be used to identify environmentally critical processes along a process chain (hot spot analysis) and to identify opportunities to improve the environmental performance of products or services at various points in their life cycle (ISO 14040, 2006).

The objective of this study is to demonstrate the application and limitations of LCA to identify hot spots of potential environmental impacts in agricultural production systems at different scales, using three case studies by the authors (Kral et al. 2015; Saylor et al., 2015; Stampfel, 2014).

Materials and methods

To identify environmental hotspots in agricultural systems, this study applies the method of life-cycle assessment (LCA; ISO 14040, 2006). LCA is a systems approach aimed at assessing as much of the potential environmental impacts of a product or system as possible. It can be defined as "a compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle." (ISO 14040, 2006). A product or product system (e.g., tractor, crop) is considered throughout the various stages of its life cycle, from the extraction of raw materials through manufacturing and use to the disposal. The method encompasses four distinct phases (ISO 14040, 2006): In the first phase, the goal and scope of the LCA are identified and described. In the second phase, a comprehensive inventory of all resource uses and emissions is established, the so-called life-cycle inventory. The third phase – the life-cycle impact assessment –

translates the inventory into their potential environmental impacts. In the interpretation phase, the results of the previous phases are structured, carefully evaluated for consistency and quality, and finally reported.

For case study 1, the system function is the provision of draught power for agricultural processes by a tractor. Therefore, the chosen functional unit – the basic quantity to which the results of an LCA are related – is one mid-sized tractor providing these services over its 24-year lifespan. The functional unit in case study 2 is one kilogram (fresh matter, FM) of maize silage at 30% dry matter (DM) content. In case study 3, the funtion of the biogas system from grass is varied, with the main outputs being heat and electricity, as well as management of the organic waste streams from the municipality and of manure. For simplicity, and to allow comparison with other biogas LCAs, a functional unit of 1 kWh of electricity output from the CHP module was chosen as a functional unit.

Case study 1 – life cycle impacts of a mid-sized tractor

This system describes the life cycle of a mid-sized tractor (Steyr Profi 4110, 81 kW rated power). An overview of the life-cycle model is shown in Figure 1.

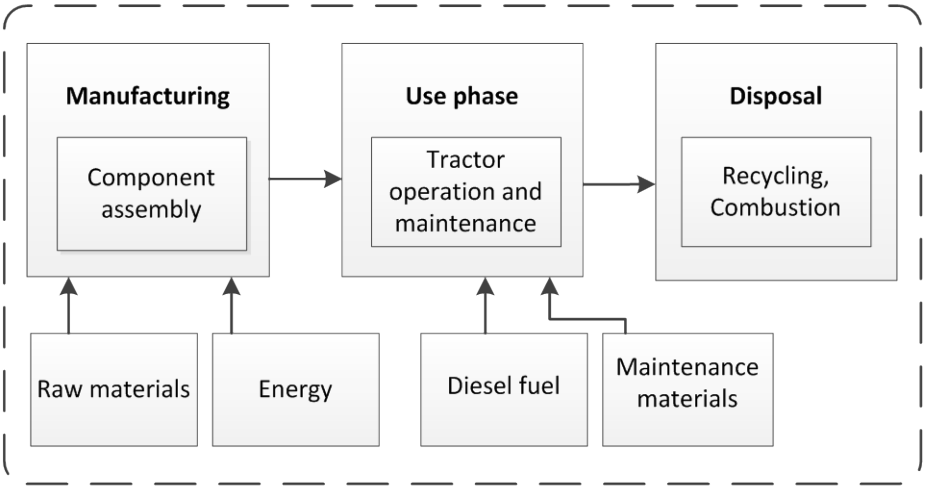


Figure 1. System diagram of the life-cycle model for the studied tractor

The LCA system includes the manufacturing, use, and disposal of the tractor, with an assumed technical lifetime of 24 years and 6747 hours of operation. The chosen model year is 2004, since data on fuel consumptions and exhaust emissions were first available for the model in that year. The manufacturing phase was modelled using primary data that include an aggregate bill of materials for the tractor components, as well as the tractor assembly plant's energy consumption. For the use phase, the tractor was assumed to be operated at an organic 140-ha farm in eastern Austria. The farm grows mixed grains in an eight-year rotation, and five farming processes (ploughing, cultivation, harrowing, baling and bale transportation; Table 1) were selected that can be performed with the tractor size studied. Fuel consumption and emissions during operation were approximated by weighted averages of individual cycles from an ISO 8178-4 C1 eight-cycle test for a tractor with a similar engine, a New Holland TS 110A with 85 kW rated power (Landis, 2004). The cycles were not weighted as prescribed in the standard, but according to field-determined load profiles by Rinaldi et al. (2005). The emission factor for diesel Particulate Matter (PM) was not determined during the ISO test cycle, but expected to behave similar to CO emissions, as both are results of incomplete combustion. Therefore, surrogate PM emission factors were estimated from CO emission factors using a constant ratio of CO to PM emission factors as determined by the manufacturer (unpublished results). The calculations yielded specific estimates of the hourly fuel consumption and air emission factors for each of the five chosen processes (Table 1).

Table 1. Cultivation processes for the studied tractor, process-specific hourly fuel use and exhaust emission factors. HC = Hydrocarbons, PM = Particulate matter

Farming process	Fuel use (kg*h^{-1})	CO_2 (kg*h^{-1})	HC (g*h^{-1})	NO_x (g*h^{-1})	CO (g*h^{-1})	PM [a] (g*h^{-1})
Ploughing, 4-furrow reversible mounted plough	12.64	39.82	10.42	304.81	34.07	6.81
Cultivation, 3 m shallow cultivator	12.57	39.61	10.82	301.85	32.20	6.44
Harrowing (seedbed preparation), harrow and packer, 3 m	13.33	42.00	11.23	316.54	35.27	7.05
Baling, round bales, 1.2 m	8.99	28.32	7.42	205.66	28.25	5.65
Bale transport, double trailer, 8 t each	4.94	15.57	5.01	115.91	20.12	4.02

[a] Estimated by scaling up CO emission factors using a constant ratio of 0.2 between CO and PM emission factors (W. Zauner, personal communication,2013).

Emission increases due to engine aging over the tractor’s life span were calculated based on Schäffeler and Keller (2008). Maintenance during tractor use was included by replacement of components according to the manufacturer’s maintenance schedule for a later model year (W. Zauner, personal communication, 2013). Engine oil, filters and filter pump are replaced every 600 hours, other oils and transmission belts every 1200 hours. During the end-of-life phase of the tractor, the main material groups were modelled with specific disposal processes. Metal components are shredded and recycled; the recycling process itself is not included in the model, but manufacturing is based on using recycled steel (closed-loop approach). Polymer components, as well as used motor oil, are combusted in a waste incineration plant.

Used tyres were assumed to be incinerated in cement kilns (60%) or shredded for re-use (40%), following ETRMA (2011).

Case study 2 – life cycle impacts of a maize silage production

The second case study describes an average production of maize silage in Austria, up to the point of storage (Figure 2). Details of the system are given in Kral et al. (2015). Briefly, the system includes all auxiliary materials, from seed production to the production of machinery and machine sheds to the transportation of auxiliary materials to the farm. The system is based on a data from the ecoinvent database (Nemecek and Kägi, 2008), with several modifications: A 15-year average Austrian maize silage yield of 45.55 t fresh matter per hectare and year (1999 to 2013; Statistik Austria, 2014) was assumed at 70% dry matter content. As the sole fertilizer, liquid digestate (159 kg N per hectare and year) from a silage/slurry-fed biogas plant was modelled. The herbicides applied were adjusted to reflect Austrian practices (BMLFUW, 2008). As is further described in Kral et al. (2015), the silage was used as the main substrate (80% of total substrate FM) of a hypothetical 500 kW_{el} biogas plant (Laaber, 2011) that generates electricity and heat through a combined-heat-and power (CHP) module.

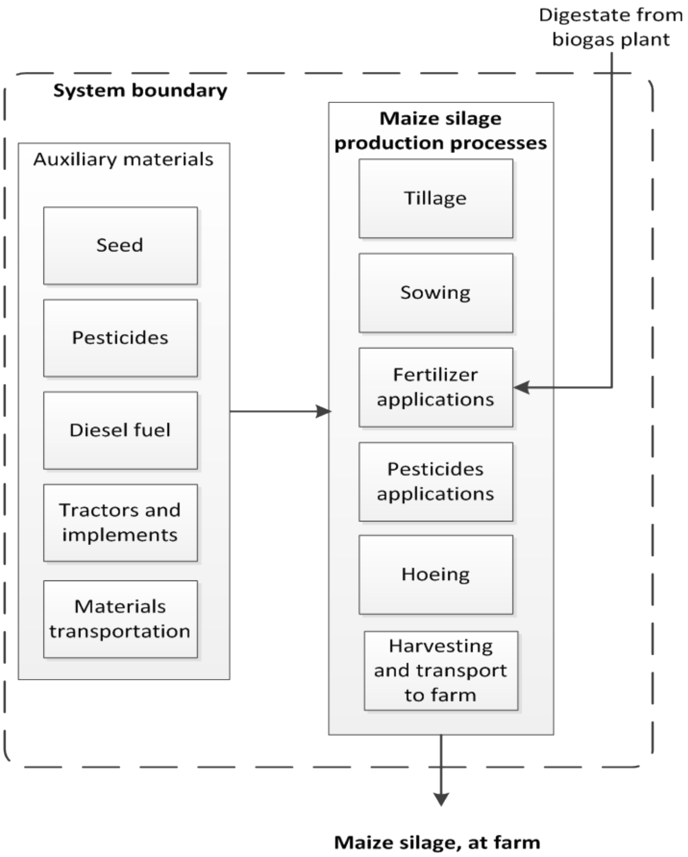


Figure 2. System diagram for an average Austrian maize silage production process, up to transportation to storage

Case study 3 – life cycle impacts of biogas electricity from grassland

The third case study describes how the hypothetical biogas plant mentioned above would be embedded into a larger system - the energy and waste management system of an Alpine municipality in Western Austria (Saylor et al., 2015). In contrast to maize silage in the previous case study, the primary biogas substrate in this scenario is grass (conserved as hay) from Alpine grasslands that are not currently in production. Other biogas substrates include green waste, municipal organic wastes, oils and fats, and solid manure (Table 2).

Table 2. Annual substrate inputs (hay, manure and other wastes) in the case study municipality. Amounts are based on requirements for a 500 kW_{el} biogas plant

Substrate inputs	Substrate	Dry matter content	Organic dry matter content	Annual CH_4 yield	Annual energy from CH_4
	[t FM*a^{-1}]	[% of FM]	[% of DM]	[Nm^3*a^{-1}]	[kWh*a^{-1}]
To biogas ferment. via steam explosion pretreatment					
Hay	3,331	87%	94%	753,573	7,505,587
Green waste	306	15%	89%	11,307	112,616
Municipal organic waste mixture	894	39%	52%	71,108	708,234
Oils and fats	36	95%	92%	21,396	213,099
Direct to biogas ferment.					
Solid manure	2,630	25%	80%	129,459	1,289,410

The entire system is shown in Figure 3. Before entering the biogas fermenters, hay would undergo steam explosion pretreatment, as would municipal organic and green wastes. Steam explosion technology is an innovative and relatively new pretreatment technology for biogas generation. It is described elsewhere in more detail (Bauer et al., 2014). Briefly, poorly digestible biomass is brought to a high temperature by adding steam in a pressurized vessel. After a retention period of typically less than one hour, the biomass-steam mixture is abruptly depressurized, hydraulically disrupting the biomass fibre structure. This improves the digestibility of lignified biomass such as agricultural residues while also having an odour reducing and sterilizing effect on organic wastes (Sargalski et al., 2007). Of the substrates listed in Table 2, solid manure would be added directly to the fermenter as no sanitation step is required. The biogas generated in the fermenters is fed into a CHP module that is assumed to operate during 7,470 hours per year, combusting 240 m^3 biogas with a 55% methane content per hour, at an electrical efficiency of 38%, and at a thermal efficiency of 42%. The relatively low efficiency assumptions reflect diminishing efficiencies with CHP age. Air emissions due to CHP operations were calculated using exhaust pollutant concentrations provided by the CHP manufacturer (T. Elsenbruch, personal communication, 2014). A methane concentration of 1200 ppm in the CHP exhaust corresponds to a methane slip of 2.6% of the methane input. All CHP electricity (3,735,000 $kWh_{el}*a^{-1}$, equivalent to 500 kW_{el} power) is fed into the local power grid, which also supplies the operational power for the site. Most of the CHP heat output (69% of 4,128158 $kWh_{th}*a^{-1}$) is assumed fed into the local district heating system where it would replace currently operating residential heaters fuelled with heating oil (2,416,042 $kWh_{th}*a^{-1}$). The remaining CHP heat is used on-site for steam explosion pretreatment and fermenter heating, totalling 575,156 $kWh_{th}*a^{-1}$, and the rest is wasted due to seasonal demand fluctuations. A portion of the fermenter digestate would be used as a fertilizer on the same grassland from which the hay was harvested and the remainder is assumed to be sold to local farmers. Some of the substrates for the hypothetical biogas plant are currently treated in a regional waste treatment plant that generates heat. If used locally in the hypothetical biogas plant, they would no longer contribute to that regional plant, and the missing heat would have to be supplied by a generic regional heat mix.

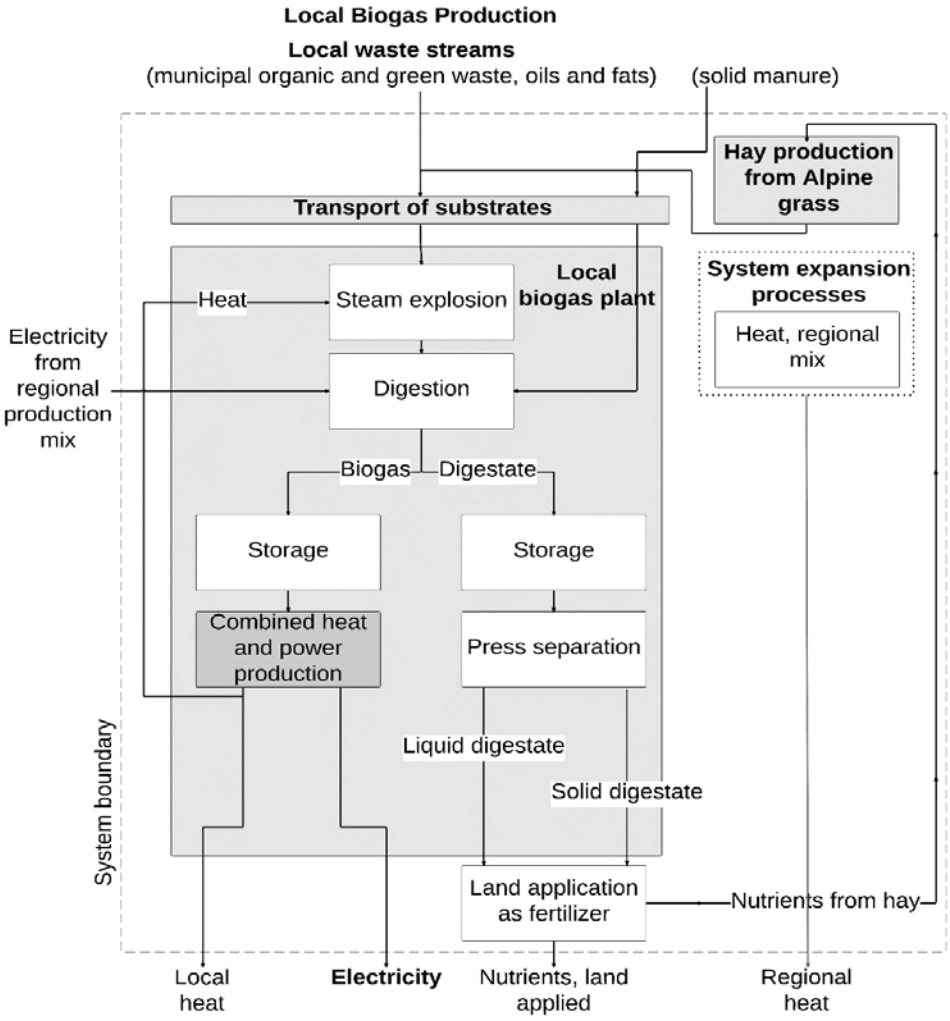


Figure 3. System diagram for local electricity and heat production from biogas. Substrates are hay from Alpine grassland and local organic wastes

The impacts of providing system infrastructure are considered in the analysis presented here. This includes materials for the biogas plant, agricultural machines for grassland management, and additional materials for the steam explosion unit. Disposal of this infrastructure was considered negligible. Grassland management processes include seeding, fertilizing, harvest and outdoor drying, and hay transport and storage. All wastes, as well as manure inputs, were modeled without upstream burdens and enter the system at the point of transportation to regional or local waste management facilities.

Data and software

LCA models were assembled using the software OpenLCA v.1.4 (Green Delta GmbH, Berlin, Germany). Potential environmental impacts were evaluated using six selected categories from the the ReCiPe (H) midpoint impact assessment method (Goedkoop et al., 2013). ReCiPe’s climate change characterization factors were adjusted to reflect the most current IPCC estimates for global warming potentials (a 100-year GWP of 34 kg CO_2-eq*kg^{-1} methane including climate-carbon interactions; IPCC, 2013). In the case of biogenic methane, the 100-year GWP of sequestered carbon was subtracted, resulting in 31.25 kg CO_2-eq*kg^{-1} methane. Leading manufacturers of the combined heat and power (CHP) generator and steam explosion pretreatment unit provided primary data on their respective technologies (T. Elsenbruch and P. J. Nilsen, personal communication, 2014). Primary data was supplemented with secondary data from literature and from the Ecoinvent database v.2.2.(Ecoinvent Centre, 2010).

Results and discussion

The following sections describe the potential environmental impacts of the three systems described above. They quantify the impacts for the chosen impact categories and identify hotspots for the climate change impact.

System 1 impacts and hot spots

Results over the tractor’s life-cycle shows that all environmental impact categories are dominated by the use phase, as indicated by the main processes that contribute to each impact category (Table 3), with 84.4% to 99.6% of the impact score.

Table 3. Potential environmental impacts of 24-year tractor life-cycle at 281 operating hours per year

	Tractor lifetime impacts (24 years)		
Impact category	Unit	Quantity	Main contributing Process
Climate change (GWP 100)	kg CO_2-eq	287,822	Diesel combustion during cultivation
Freshwater ecotoxicity	kg 1,4-DCB-eq	329	Diesel extraction and refining
Human toxicity	kg 1,4-DCB-eq	12,609	Diesel extraction and refining
Particulate matter formation	kg PM10-eq	555	PM emissions during diesel comb.
Terrestrial acidification	kg SO_2-eq	1,335	NOx emissions during diesel comb.
Non-renewable energy resources	MJ-eq	4,182,198	Diesel use for cultivation processes

Manufacturing the tractor, which includes the production of the materials and final assembly, causes 0.4 to 12.1% of the impact scores, depending on the specific impact category. This result is in agreement with Lee et al. (2000), who found that 85% of a small (28 kW) tractor’s total environmental impact score was due to the use phase, with 11.3% due to manufacturing and distribution, and the remainder due to the end-of-life disposal of the tractor. Within the use phase, supplying and combusting diesel fuel causes most impacts, while maintenance is of secondary importance.

Within the category climate change (GWP100), the fuel-intensive tillage processes (ploughing, harrowing, cultivating) were by far the largest contributors, with 55%, 13%, and 10% of the category total (Figure 4).

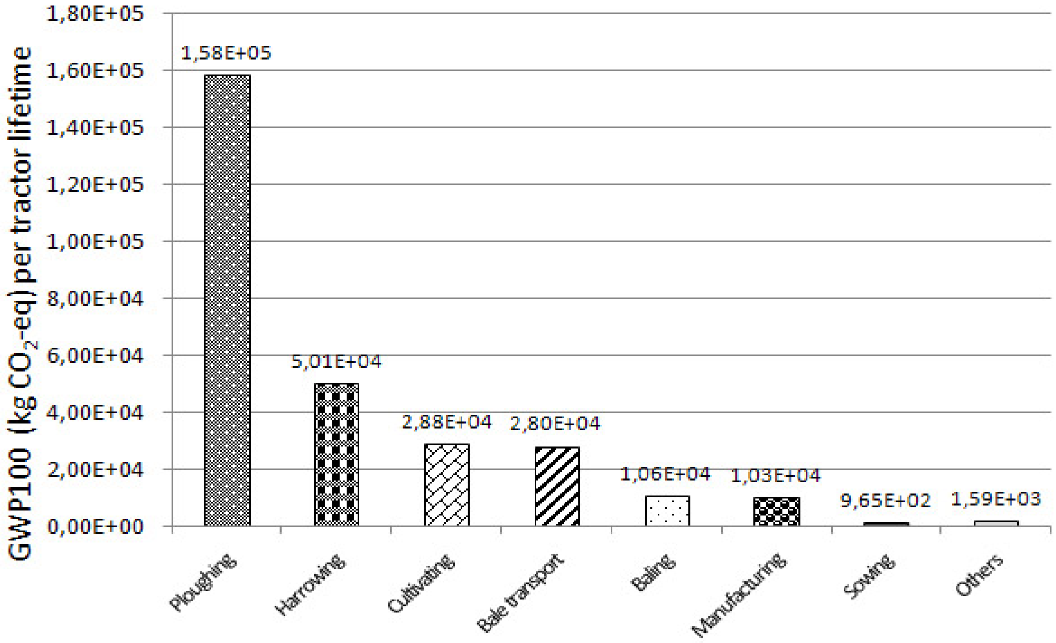


Figure 4. Contribution of individual processes to total climate change impact of tractor life-cycle

System 2 impacts and hot spots

The production of maize silage under typical Austrian conditions shows low impacts in the climate change category (Table 4), but impacts in the terrestrial acidification category due to ammonia emissions during digestate application are within the range of literature. This is in comparison with Dressler et al. (2012), who report for maize cultivation at three German study sites a GWP of 0.0454-0.0577 kg CO_2-eq, but an acidification potential of 0.00026-0.00037 kg SO_2-eq per kg maize (FM). An evaluation of conventional maize silage production as modeled in the Swiss Ecoinvent database (Ecoinvent Centre, 2010) yields a higher GWP of 0.0531kg CO_2-eq, and a higher acidification potential of 0.00117 kg SO_2-eq per kg maize (FM) as well.

Table 4. Potential environmental impacts of typical maize silage production per ha cropland and per kg silage (fresh matter)

Impact category	Unit	Potential impact		Main contributing Process
		per hectare[a]	per kg FM	
Climate change (GWP 100)	kg CO_2-eq	1,057	0.0232	Harvesting maize, diesel emissions
Freshwater ecotoxicity	kg 1,4-DCB-eq	2,151	0.0472	Herbicides application
Human toxicity	kg 1,4-DCB-eq	345	0.0076	Zinc in digestate[b]
Particulate matter formation	kg PM10-eq	28	0.0006	PM emissions, digestate application
Terrestrial acidification	kg SO_2-eq	197	0.0043	NH_3 emissions, digestate application
Non-renewable energy resources	MJ-eq	11,735	0.2576	Harvesting maize, diesel emissions

[a] 15-year average Austrian yield of 45.55 t FM*ha^{-1} (Statistik Austria, 2014).

[b] Zinc in digestate originates mainly from feed in pig slurry that is assumed to be a co-substrate in digestate production.

A contribution analysis specifically of the climate change category (Figure 5) shows the dominance of the most fuel-intensive processing step, the harvesting (and chopping) of the silage maize with a forage harvester, followed by digestate application that is associated with emissions of the greenhouse gases nitrous oxide and methane (0.0057 g CO_2-eq per kg FM silage, or 24% of total GWP100). The other contributors to the GWP100 score are again various processes of sowing, tillage, and seedbed preparation (harrowing); Total CO_2 emissions from tractor and forage harvester operations account for 0.0148 kg CO_2-eq per kg FM silage, or 64% of the total score.

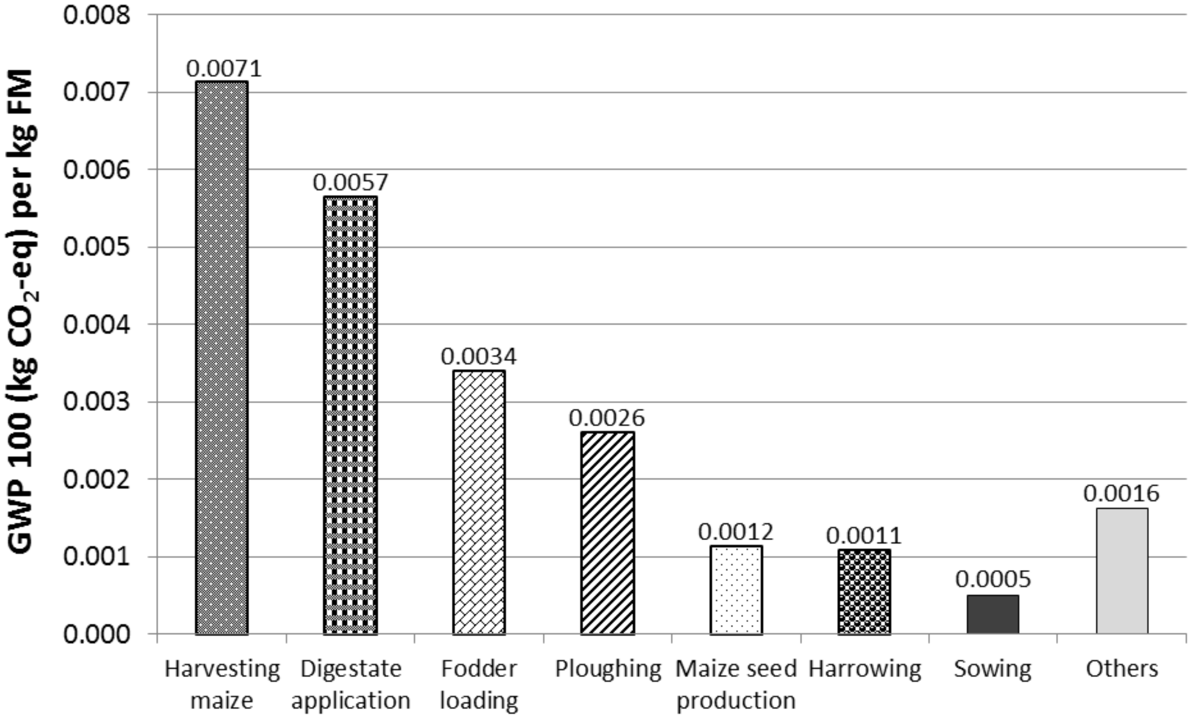


Figure 5. Contribution of individual processes to total climate change impact of producing 1 kg FM maize silage

Maize silage is one of the most popular energy crops for biogas production through anaerobic fermentation. Supplying the required amount of maize silage (10,714t FM on 235 ha) as a substrate for electricity from a 500-kW_{el} biogas plant contributes 22% to the total climate change impacts (GWP100) of 299 g CO_2-eq*kWh^{-1} biogas electricity production (Kral et al. 2015) The dominant contribution to GWP100 in this wider system are methane emissions in the CHP exhaust, at 48% of the total score.

System 3 Impacts and hot spots

In the third case study, a more complex system models the impact of establishing a biogas plant in an Austrian Alpine municipality. The plant would use grass (hay) and various organic wastes and solid manure, supplying electricity to the regional grid and heat to an existing local district heating network. The LCA analysis of the selected potential impacts (Table 5) shows that hotspots in this system are varied. Similar to the silage-based biogas model in the previous case study, the climate change category is dominated by methane slip, while other contributions are dominated by raw materials (diesel fuel, copper for infrastructure) acquisition and digestate emissions.

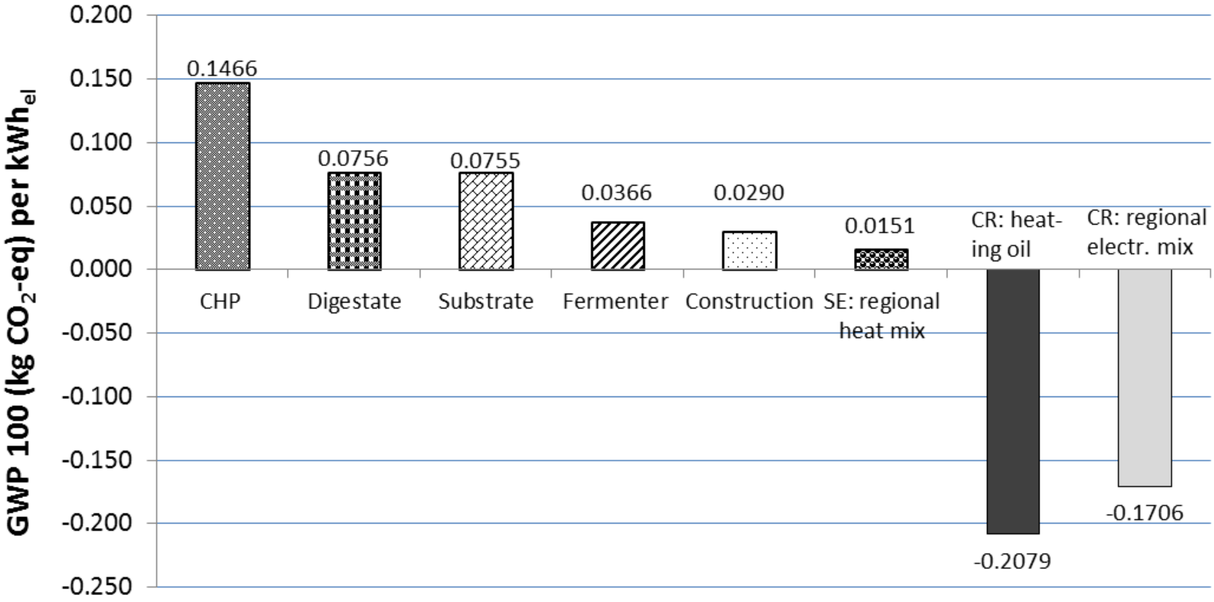
Table 5. Potential environmental impacts and main contributing processes of biogas production from grass and organic wastes in a 500-kW_{el} biogas plant in an Alpine Austrian municipality

Impact category	Unit	Potential impact per kWh_{el} from biogas[a]	Main contributing Process
Climate change (GWP 100)	kg CO_2-eq	3.78E-01	Methane slip in CHP exhaust
Freshwater ecotoxicity	kg 1,4-DCB-eq	5.35E-05	Diesel extraction and refining[b]
Human toxicity	kg 1,4-DCB-eq	1.98E-02	Copper in construction materials
Particulate matter formation	kg PM10-e	2.14E-03	PM emissions, digestate application
Terrestrial acidification	kg SO_2-eq	4.35E-05	NOx emissions, digestate application
Non-renewable energy resources	MJ-eq	2.23E+00	Diesel use for hay production

[a] Numbers without credits for heat and electricity replaced by the output from the local biogas plant.

[b] Diesel is mainly used here for grass/hay production.

The hot spot analysis of climate change contributions (Figure 6) shows that digestate application and grass/hay production are the largest contributors after the aforementioned methane emissions in the biogas CHP exhaust. Figure 6 also shows a small contribution from a (hypothetical) mix of regional heat sources (approximately 50% natural gas, 20% each of fire wood and heating oil, and electricity providing the balance). This heat is necessary to account for missing heat that is no longer generated through organic wastes treatment in a regional centre, since these wastes are now substrates for the local biogas plant. In contrast to the climate change score listed in Table 5, Figure 6 includes a depiction of “credits” for the biogas plant’s outputs – the energy replaced by electricity and heat from biogas can be counted as large (negative) contributions, with net “negative” emissions. A clearer picture is obtained by setting up a proper reference system that reflects the status quo of the current management scheme for organic wastes (grassland is not being used at this time). This reference system shows a GWP100 of 0.451 kg CO_2-eq*kWh_{el}^{-1}, in contrast to the local biogas production with a GWP100 of 0.378 kg CO_2-eq*kWh_{el}^{-1} (Saylor et al., 2015).



SE = System expansion process, to account for missing heat that is no longer generated through off-site organic wastes treatment. CR = credits for oil-based residential heaters and regional electricity demand that are displaced by the heat and electricity from the local biogas plant

Figure 6. Contribution of individual processes to total climate change impact of producing 1 kWh_{el} from biogas with grass/manure and organic wastes as substrates

Synopsis of hot spots and mitigation options

The analysis of hot spots can point out mitigation options for environmental impacts of the agricultural systems shown. In case study 1, the clear focus of mitigation efforts for a tractor’s life-cycle impacts has to be in efficiency measures and exhaust controls. Renewable fuels such as biodiesel and vegetable oils may also assist in reducing some of the analysed impact scores, but not all. In case study 2, both efficiency increases in agricultural machinery and attention to favourable conditions during fertilizer application constitute classical results of agricultural crop LCA. Finally, case study 3 demonstrates that agricultural systems – if seen as part of an agromunicipal infrastructure – may not be the only drivers of substantial environmental impacts of such larger systems. Here, the type and emissions from heat sources that are replaced by biogas heat are key considerations for analysis. Thus the hotspot analysis presented here shows that growing system scales retain key hotspots, such as machinery use, but they also add new ones, with no clear trend perceivable. Beyond the impact categories discussed, there are environmental problems in agriculture that are not well described by the common impact categories (for example impacts on biodiversity, soil quality, and water availability; Caffrey and Veal, 2013). Such impacts are beginning to be addressed by emerging categories, but are not yet fully integrated in the available life cycle databases or are just difficult to quantify by a broad method such as life cycle assessment.

Conclusions

- Life cycle impacts of a mid-sized tractor are dominated by fuel use and emissions during its use phase; tractor manufacturing and disposal contribute considerably lower shares to total impacts.
- When tractors and other machinery are used in the production of an energy or fodder crop such as maize silage, the impacts from operation of agricultural machinery are still important in categories such as climate change and non-renewable energy demand. In other categories however, fertilizer and pesticides applications can dominate the score.
- At a larger system scale, environmental hotspots grow even more diverse; with the studied biogas system, methane emissions from the CHP engine surpass the impact of agricultural machinery in the climate change category, at 48% of the total GWP100 score. Infrastructure materials and digestate application are also important at a larger scale.
- The net impact of a new biogas system that uses Alpine grasslands depends critically on the energy system that it replaces. Under the assumptions made here, this system compares favourably with a status quo that on one hand relies on centralized treatment of organic wastes in a regional centre and on the other hand fails to use Alpine grassland as a source of biomass.
- Efforts to mitigate environmental hotspots will strongly depend on the scale of the studied system; hotspots in more narrowly defined systems such as single crop production may lose their relevance in larger systems.
- The case studies presented here demonstrate the potential and limitations of LCA as a technique that supports decisions by stakeholders in agricultural and agromunicipal systems. Choosing an appropriate system scale is key to a successful application of this method.

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