

Environmental Life-Cycle Assessment of Arable Crop Production Technologies Compared to Different Harvesting Work Systems in Short Rotation Energy Plantations

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Abstract – Environmental life cycle assessment (LCA) was developed as a tool for sustainable, decision-supporting environmental management. Applying agricultural sector-LCA in order to achieve both internal (comparative) and external (efficiency enhancing) benefits is a priority. Since the life-cycle assessment of products and processes attracts great interest, applying the method in agriculture is relevant. Our study undertakes a comparative environmental life-cycle assessment (LCA) of local arable crop production technologies used for the main cultivated plants: maize, sunflower, lucerne, cereals, and canola (environmental data in the territorial approach calculated on a 1 ha unit and in the quantitative approach calculated on 1 t of produce). We prepared an environmental inventory of the arable crop production technologies, constructed the life-cycle models, and executed the impact assessment. We also compiled an environmental ranking of technologies. In the impact interpretation, we compared the results with the values of short rotation energy plantations in each impact category. We analysed carbon footprints closely. The obtained results help better assess environmental impacts, climate risks, and climate change as they pertain to arable crop production technologies, which advances the selection of appropriate technologies adjusted to environmental sensitivities.

environmental life cycle assessment / carbon footprint / arable crop harvesting technologies / global warming potential

Kivonat – Szántóföldi növénytermesztés környezeti életciklus elemzése. A környezeti életciklus-elemzést (LCA) fenntarthatósági, döntéstámogató környezetmenedzsment eszköznek fejlesztették ki. Az LCA alkalmazása az agrárszektorban mind a külső (összehasonlító), mind a belső (hatékonyságnövelő) előnyök elérése érdekében is prioritás. Mivel a termékek és folyamatok életciklus elemzését nagy érdeklődés övezi, ezért e módszer mezőgazdasági alkalmazásának mindenképpen el kell terjednie. Kutatásunkban a hazai szántóföldi növénytermesztési technológiák (kukorica, napraforgó, lucerna, kalászosok, repce) összehasonlító környezeti életciklus-elemzésére vállalkoztunk (területi megközelítésben: környezeti adatok 1 ha-ra vetítve és mennyiségi megközelítésben: környezeti adatok 1 t-ra vetítve). Előállítottuk a szántóföldi növénytermesztési technológiák környezeti leltáradatbázisát, felépítettük az életciklus modelleket és elvégeztük a hatásértékelést. A technológiák környezeti rangsorát is felállítottuk. A hatásértelmezés során a kapott értékeket rövid vágásfordulójú energiaültetvényeknél tapasztalt értékekkel hasonlítottuk össze hatáskategóriánként. Kiemelt figyelmet fordítottunk a szénlábnyom elemzésére. Az

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eredmények ismerete segíti a szántóföldi növénytermesztési technológiák esetén a környezeti hatások, a klímakockázatok és a klímaváltozásban betöltött szerep helyesebb identifikálását is. Ez segítheti a környezet érzékenységéhez illeszkedő megfelelő technológiák kiválasztását is.

életciklus-elemzés / szénlábnyom / szántóföldi betakarítási technológia / globális felmelegedési potenciál

1 INTRODUCTION

The fundamental economic performance changes in the production sector have been major causes of environmental problems since the Industrial Revolution. Nevertheless, the production sector, which includes the agricultural sector, would also be the easiest to control. Numerous regulatory principles have already been developed; of these, the voluntary principles (including life-cycle assessment, ISO (2006a), ISO (2006b)) are able to provide an effective, proactive approach to the management of environmental problems (Rédey 2011). Applying agricultural sector-LCA to achieve both internal (comparative) and external (efficiency enhancing) benefits is a priority. Since the life-cycle assessment of products and processes attracts great interest, applying the method in agriculture is pertinent.

Haas et al. (2000) examined the applicability of the LCA framework at the farm level. Numerous further studies proving the importance of applying LCA in the agricultural sector have been recognized (Nemecek et al. 2006, Rodrigues et al. 2009, and Dauguet et al. 2016). Several review articles address the challenges and perspectives involved in the application of the methodology (Hayashi et al. 2005, Harris – Narayanaswamy 2009, Caffrey – Veal 2013). Only 11–13% of the Earth's surface is cultivated; however, cultivation is not intensive in the majority of these areas. In contrast, 50% of Hungary's land area is intensely cultivated, while intensively managed forests cover another 20% of the country (Neményi – Milics 2010). About 75% of Hungary's surface area is occupied by primarily climate-dependent, non-irrigated land, which includes arable land, meadows, and forests. In addition to growing conditions altered by cultivation techniques and land cover effects, the specific environmental aspects of each utilized technology have to be considered for each land use type.

As noted above, crop production occurs on about half of Hungary's land area, which amounts to approximately 4.5 million hectares (KSH 2018). Nearly one-third of this area is poor-quality arable land where agriculture would be uneconomical. Energy plantations can be grown extremely well on poor-quality land. Currently, the carbon neutrality of wood as a raw material must also be justified, considering several factors (Polgár et al. 2018).

Yield fluctuations in the arable crop production in Hungary extend beyond what can be considered reasonable. These fluctuations can be attributed partly to climate, partly to soil quality, partly to technology, and partly to low irrigation capacity. Main crop yields are near levels recorded two or three decades ago (OTP 2017).

According to Nagy (2018), future agriculture will be characterised by the climate crisis, the increasing demand for food products, digitalisation, precision farming, and the spread of robotic innovations. The world will need 70% more food in 2050. This will coincide with the climate crisis, which could lead to a 30% decrease in arable land and a 40% decrease in potable water. Only science can address these challenges.

Maintaining an environmental balance and reducing damage caused by climate change anomalies are the two basic pillars of sustainable agricultural competitiveness. Therefore, irrigation, agrarian digitalisation, and the generational replacement of farmers will be more vigorously supported (Nagy 2019).

Nonetheless, several authors note that the arable production of biomass can only remain viable if the technologies applied meet environmental and sustainability requirements. Dinya

(2018) emphasizes the importance of long-term and supply chain-sensitive decision making, which prioritises technical aspects and is integrated into the wider system at both local and national levels. The life-cycle assessment method can be applied to environmental impact evaluations. This method provides accurate estimations for the emissions and energy balance of all biomass-producing and biomass-consuming methods (Heller et al. 2003). Hayashi et al. (2007) examined the schematic processes of agricultural production systems in the life-cycle approach. In addition to the environmental impacts of the primary processes, the study emphasised the need to identify background processes as well.

In our study, we have undertaken the comparative environmental life-cycle assessment (LCA) of the local arable crop production technologies used for the main cultivated plants (maize, sunflower, lucerne, cereals, and canola), taking environmental data into account in the territorial approach calculated on 1 ha unit and in the quantitative approach calculated on 1 t of produce.

Our research questions are as follows: What are the main environmental impacts of the cultivation technologies applied in the studied agricultural land uses? How does the environmental ranking of cultivation technologies evolve? To what extent do they contribute to the climate change? What is the expected carbon footprint of cultivation technology (in the territorial approach: 1 ha; and in the quantitative approach: 1 t)? How do these technologies relate to other biomass producing systems?

Polgár et al. (2018) forms the basis of comparison between cultivation technologies and other biomass producing systems. The study conducted a comparative environmental life cycle assessment for harvesting technologies of short rotation energy plantations (technology related to stands of 3 ha of poplar, 5–10 ha of willow, 20 ha of willow), specifically for the third year harvesting work system.

2 MATERIALS AND METHODS

The methodology applied for completing LCA corresponds to the requirements of ISO 14040: 2006 and ISO 14044: 2006 standards. The analysis was completed using GaBi 6.0 Professional (GaBi Thinkstep 2018) software. The required steps of LCA were the following: 1. Definition of goal and system boundaries. 2. Life cycle inventory analysis. 3. Impact assessment. 4. Impact interpretation (ISO 2006a, ISO 2006b).

Goal: The goal of the comparative LCA is to answer the preceding research questions in relation to the arable crop production technologies by applying the assessment methodology.

System boundaries: The examined life-cycle stages were determined by the specific technologies and the operational steps associated with them. The common field operations are: soil preparation – application – sowing – pesticide application – harvest – product transport – storage. In addition to the processes above, we also considered the background processes of fuel and lubricant oil production when calculating environmental impacts. The transport distance was uniformly considered as 10 tkm. A distance of 5 km of road travel in each direction was calculated for additional service transport.

Detailed processes and operational steps included in the main cultivated plants:

- Cereals (forecrop: sunflower): stubble cleaning by gruber – subsoil loosening – fertiliser application – seedbed preparation – sowing – top dressing – pesticide application – top-dressing – pesticide application – spica protection – harvest – product transport – storage
- Maize (forecrop: winter wheat): stubble cleaning by gruber – autumn deep ploughing – spring ploughing work – seedbed preparation – sowing + fertiliser application – pesticide application – row tillage – harvest – product transport – storage

- Sunflower (forecrop: winter wheat): stubble cleaning by gruber – autumn deep ploughing – spring ploughing work – fertiliser application – seedbed preparation – Sowing – pesticide application – row tillage – pesticide application – desiccation – harvest – product transport – storage
- Lucerne (forecrop: cereals): stubble cleaning by gruber – subsoil loosening – fertiliser application – seedbed preparation – rolling – sowing – fertiliser application – mowing – rotation – rotation – windrowing – baling – transport – storage – mowing – rotation – rotation – windrowing – baling – transport
- Canola (forecrop: cereals): stubble cleaning by gruber – subsoil loosening – fertiliser application – seedbed preparation – rolling – sowing – rolling – spraying – spraying – spraying – fertiliser application – spraying – spraying – spraying – spraying – harvest – transport

Our research did not cover the various processes associated with the grain drying life cycle stage. The reasons we did not analyse this in our work are many. On one hand, this stage belongs to a different economic partner, which made it difficult to discover the relevant data. On the other hand, our original goal was to detect the environmental impacts in connection to local agricultural land use only. If we had also studied grain drying, we would have been unable to make a comparison with other alternative local agricultural land use (in our case the short rotation energy plantations) because the system boundaries would have differed greatly.

Life cycle inventory analysis: The environmental inventory data of arable crop production technologies were collected according to the cultivated plants studied. We established the environmental inventory database (input-output, elementary flow) for the operational steps of technologies.

Functional unit: basically, the environmental data reference was applied to 1 ha of the cultivated area according to the territorial approach. Whereas with a view to a more nuanced presentation, the reference unit was 1 t of produce according to the quantitative approach. The *reference flows* related to specific cultivated plants are shown in detail in the inventory database of the territorial approach (*Table 1*).

With environmental inventory data, we considered the common period of process steps (for annual cultivated plants: 1 year) as a reference period. With the operational steps of the common three-year operational period of lucerne as a multi-annual crop, the whole period values of repetitive operations were divided into three parts to allow a comparison with annual plants.

The reference period for the data: 2016. *The geographical validity* of the data is national, specific to the area of Pápa.

The area of Pápa belongs to the Pápa-Devecseri Plateau (Pápa-Devecser sík), which is located between Bakony and Marcal valley. Brown forest soils are characteristic in the area (luvisols (36%); brown earth (21%); chernozem brown forest soil (13%). Meadow soils are typical in the floodplains. Most of the surface is covered by loess-muddy-sandy river water and slope deposits. Sand and pebble Pliocene material appears on the surface in many places. The northern region of this area is moderately warm and dry while the southern region is moderately wet (Dövényi 2010). Precipitation in the reference period was higher than average: 645 mm for the all whole year and 325 mm during the vegetation period. The average annual hours of sunshine is approximately 1950 hours. According to the Meteorological Database of US-FF-IEES (2016), the average temperature was 11.2°C in 2016. Temperatures averaged 17.6°C during the vegetation period. The aridity index is between 1.14 and 1.18. Days with snow cover numbered 40. The dominant wind direction is north. The arable crop production economic area was 140 ha (*Figure 1*). This type of climate is favourable for cereals, maize, sunflower and red clover.

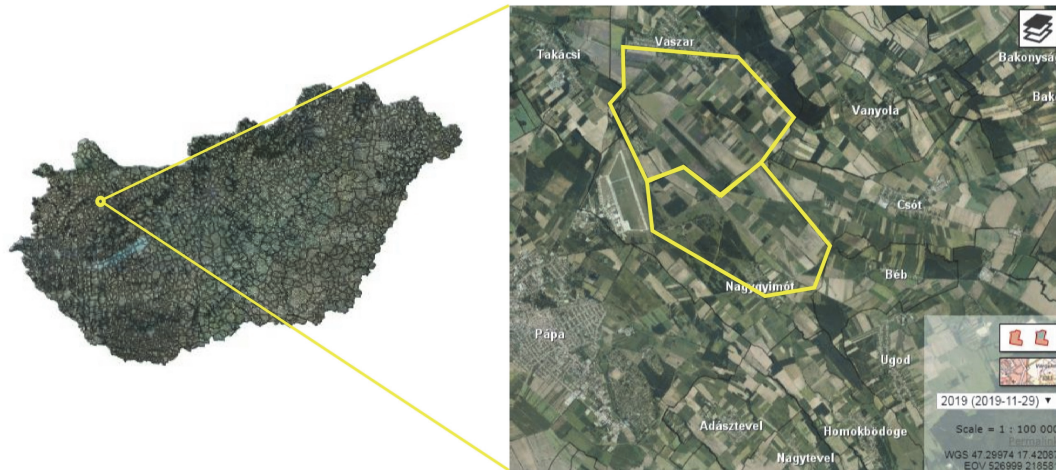


Figure 1. Economic area of arable crop production, Pápa area, Hungary (MePAR 2019)

The data sources stem from our own data (chemicals used: agri-business management log; fuel used: fuel bills), expert estimations (yields of crops), and published data (manuals). According to Gockler (2014), we also used average data, which were occasionally erroneous; however, their use is essential for the analysis.

In the absence of available information, the following are not included in the analysis: the environmental parameters in the machine and tool production needed for the technologies, and the impacts of road building and land use changes.

Based on the above, we constructed the software model for the life-cycle of the examined technologies.

Impact assessment: According to the standard, we first assigned the inventory results to impact categories according to the aim and frames of the LCA study. A wide range of impact evaluation methods exist. In our study, we applied the most widespread approach of the CML 2001 (January 2016) impact assessment method. This method is advantageous because it is specifically appropriate for representing carbon footprint (Simon 2012). We ranked the technologies based on the increasing values of their environmental impact.

As an impact assessment step recommended by the standard, we completed the normalisation to Central Europe with GaBi software according to the CML2001, Experts IKP (Central Europe) method in order to represent the overall environmental impact.

We also examined the CO₂ equiv. emission profiles of the related process step in order to analyse the operational contribution to the total technological carbon footprints of the specific cultivated plants according to field operation inventory results, product transport, and additional service transport.

Impact interpretation: In the last phase of the LCA, we verified the inventory analysis and impact assessment results; furthermore, we established our conclusions.

The results were examined according to both the territorial (1 ha) and the quantitative (1 t) approach. The cultivated plant values were compared to similar LCA results of other (wood) biomass producing agricultural land use technologies; namely, the observations in the 3rd year cutting age of the different (plantation size determined) harvest technologies in short-rotation energy plantations. Energy plantations provide a good opportunity for comparison because they grow extremely well on poor-quality land. Polgár et al. (2018) carried out their fieldwork in short rotation hybrid poplar and willow energy plantations in Hungary planted in single or twin rows. They separated the harvesting work systems based on the categories of the area, which are the following: large (above 20 ha), medium (5 to 10 ha) and small (below 3 ha). The plantations are harvested 3 to 5 times through a return period of 3 to 5 years

depending on site conditions and tree species. The study utilized the life cycle assessment to determine the common resulting environmental impacts of the harvesting work system at the 3-year cutting age. The study also analysed the most ideal conditions of mechanisation (Polgár et al. 2018).

3 RESULTS

In the life-cycle inventory analysis, we defined the process specific input-output data, i.e. the elementary flows. We have summarized both the input and output data. Environmental inventory data expressed per 1 ha in the territorial approach are displayed in tabular form (Table 1).

Table 1. Total input and output environmental inventory data of operations systems in the territorial approach (1 ha) by specific cultivated plants (area of Pápa, Hungary)

Factor	Unit	Cultivated plant					
		Cereals	Maize	Sunflower	Lucerne	Canola	
Reference period	year	2016	2016	2016	2016	2016	
Reference flow	t/ha	8	9	3	5	3	
Input							
Fuel	Diesel (operational + additional service)	kg	110.88	82.32	105.84	97.04	123.01
	Diesel (road traffic)	kg	35.70	26.88	29.82	44.10	50.40
	Total Diesel	kg	146.58	109.20	135.66	141.14	173.41
Lubricant	Lubricant	kg	0.59	0.58	0.59	0.18	0.61
Fertiliser	Urea (N 46%)		0.00	0.00	0.00	100.00	0.00
	Lime-ammon-saltpetre fertiliser, N (27%)	kg	500.00	300.00	0.00	250.00	250.00
	Complex fertiliser (NPK)	kg	300.00	0.00	0.00	0.00	400.00
	P fertiliser (superphosphate, P ₂ O ₅ 18%)	kg	0.00	0.00	200.00	0.00	0.00
	K fertiliser (KCl, K ₂ O 60%)	kg	0.00	0.00	200.00	0.00	0.00
Pesticide application	Herbicide	kg	0.05	0.08	2.69	0.00	0.22
	Fungicide	kg	1.01	0.00	0.61	0.00	0.25
	Insecticide	kg	0.00	0.00	0.00	0.00	0.36
	Regulator (growth regulator)	kg	0.00	0.00	0.00	0.00	0.24
	Water	l	600.00	200.00	600.00	0.00	1400.00
Output							
Atmospheric emission	Carbon-dioxide equiv. (operational + additional service)	kg	349.80	259.70	333.90	306.14	388.06
	Carbon-dioxide equiv. (road transport)	kg	112.63	84.80	94.08	139.13	159.00
	Total carbon-dioxide equiv.	kg	462.43	344.50	427.98	445.27	547.06
Waste oil	Waste oil (recycled)	kg	0.59	0.58	0.59	0.18	0.61

The use of fuel and lubricating oil (to operate the machines), fertiliser (urea, lime-ammon-saltpetre, NPK, P, K), pesticides (herbicides, fungicides, insecticides, regulators), and water were significant on the input side in operations systems, while on the output side, the CO₂ equiv. emission and waste sump oil (recycled) were significant.

For comparison, according to Polgár et al. (2018), fuel and lubricating oil consumption were significant environmental factors in harvesting work systems on the input side per 1 ha of short rotation energy plantations during winter in third-year stands in 2015–2016 (on 100 m³ of standing wood for harvesting). On the output side, the emission of CO₂ equiv. and waste sump oil (recycled) turned out to be significant. Timber is exclusively utilized for wood chips in the study. The study considered the CO₂ equiv. emissions from fuel, firewood, and slash burning. The amount of CO₂ equiv. emissions from firewood and slash burning is nearly three times higher than the amount of CO₂ equiv. emission from fuel.

The machines applied in arable crop production were mostly similar. Observable differences occurred in usage intensity of some crops (e. g. difference in soil preparation according to previous cropping).

In the following, we answer our research question through our obtained results.

Question: *What are the main environmental impacts of the cultivation technologies applied in the studied agricultural land uses? How does the environmental ranking of these technologies evolve?*

The following results were based on CML2001 (Jan. 2016) environmental life cycle impact assessment of work systems (Table 2).

Table 2. Environmental impacts of examined systems based on CML2001 (Jan. 2016) assessment method in the territorial approach (1 ha)

Environmental impact category (CML2001 – Jan 2016)	Cultivated plant				
	Cereals	Maize	Sunflower	Lucerne	Canola
Abiotic Depletion (ADP elements) [kg Sb eq.]	5.37E-05	4.00-05	4.97-05	5.16-05	6.35-05
Abiotic Depletion (ADP fossil) [MJ]	6.90E+03	5.13E+03	6.38E+03	6.62E+03	8.15E+03
Acidification Potential (AP) [kg SO ₂ eq.]	0.26	0.19	0.24	0.25	0.31
Eutrophication Potential (EP) [kg Phosphate eq.]	0.05	0.04	0.04	0.05	0.06
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	2.87	2.14	2.66	2.76	3.40
Global Warming Potential (GWP 100 years) [kg CO ₂ eq.]	505	376	467	486	597
Global Warming Potential, excl biogenic carbon (GWP 100 years) [kg CO ₂ eq.]	535	399	495	515	633
Global Warming Potential (GWP 100 years), techn. processes only [kg CO ₂ eq.] / 1 ha	462.43	344.50	427.98	445.27	547.60
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	20.20	15.00	18.70	19.40	23.90
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	7.20E+03	5.36E+03	6.67E+03	6.91E+03	8.51E+03
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	1.09-11	8.12-12	1.01-11	1.04-11	1.29-11
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	0.04	0.03	0.04	0.04	0.05
Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	0.99	0.74	0.92	0.95	1.17

Arable crop production technologies had the greatest impact on marine aquatic ecotoxicity pot. (MAETP) and abiotic depletion pot. ADP fossil had the second greatest impact. Technology impact on global warming (GWP 100) ranked third. Fuel and lube inputs and the environmental impact of fuel and lube production explains this. Due to the nature of the technologies, the impact categories of acidification pot. (AP), eutrophication pot. (EP), freshwater aquatic ecotoxicity pot. (FAETP inf.), photochemical ozone creation pot. (POCP)

and terrestrial ecotoxicity pot. (TETP inf.) were significant. The life cycle share of the technologies can be considered nearly equal (15–21%). We can establish the following increasing environmental ranking: maize (15%) – sunflower (19%) – lucerne (20%) – cereals (21%) – canola (25%).

In the total environmental impact calculation, the results of all impact categories can be demonstrated simultaneously in one dimensionless indicator per cultivated plant. We normalised the values we obtained in the compulsory impact assessment step for Central Europe (through the CML2001, Experts IKP method (Central Europe)) (Figure 2).

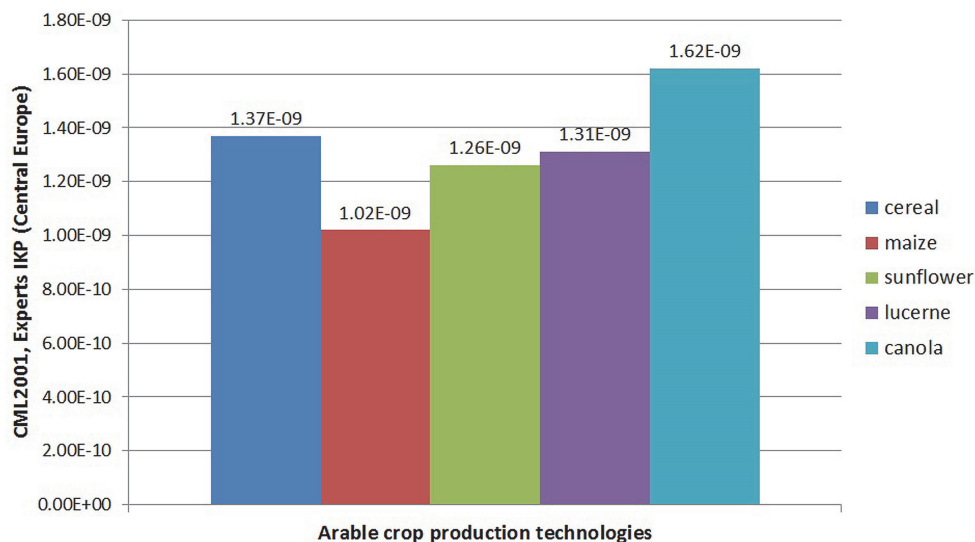


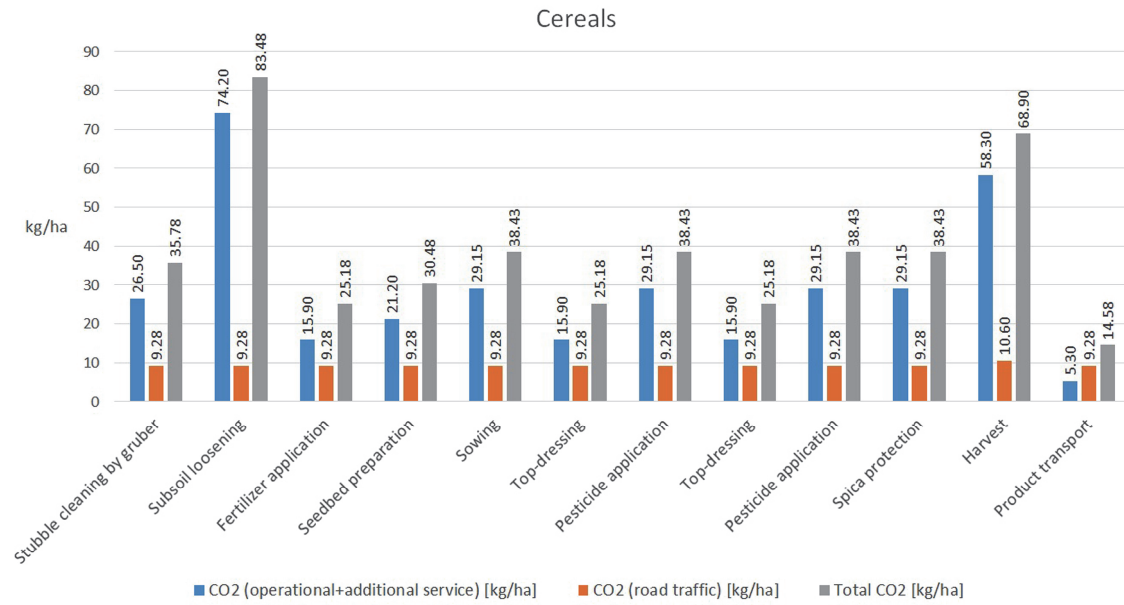
Figure 2. Total environmental impacts of the arable crop production technologies (by the method of CML2001, Experts IKP (Central Europe)) in the territorial approach (1 ha)

Through this, the previous environmental ranking of the contribution of specific cultivated plants was also confirmed as regards the total environmental impact: ‘maize (1.02E–09) – sunflower (1.26E–09) – lucerne (1.31E–09) – cereals (1.37E–09) – canola (1.62E–09)’.

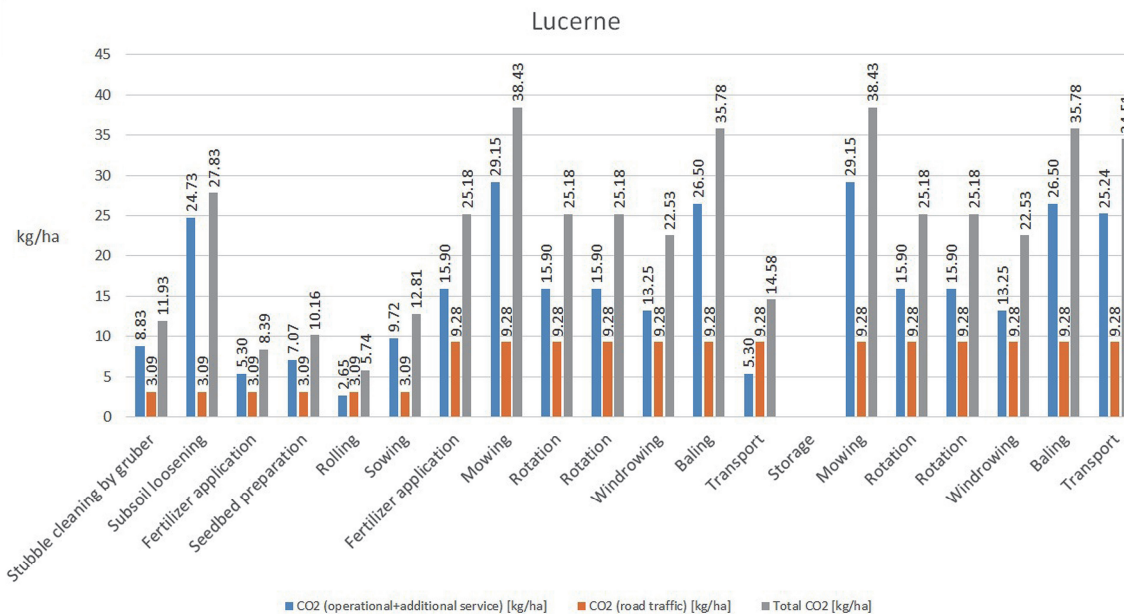
Question: To what extent do they contribute to the climate change? What is the expected carbon footprint of cultivation technology (in the territorial approach: 1 ha)?

To illustrate the contribution to climate change, we highlighted the global warming potential (GWP 100 years) values (carbon footprint) from the CML2001 (Jan 2016) impact assessment. When the carbon footprint contribution of cultivation technologies is expressed in percentages, the following increasing technological ranking emerges in the territorial approach (1 ha): maize (15%) – sunflower (19%) – lucerne (20%) – cereals (21%) – canola (25%). With the same expressed in measurement units [kg CO₂-equiv./ha], we obtained the following increasing technological ranking: maize (376 kg) – sunflower (467 kg) – lucerne (486 kg) – cereals (505 kg) – canola (597 kg).

We gained a largely coherent picture when examining the CO₂ equiv. [kg/ha] emission profile of the specific process steps (Figure 3-4). *Emission group 1:* in the case of cereals, maize, sunflower, and canola, the emissions related to the process steps occurred in a larger extent during the preparation processes of the area and during the harvest. In contrast, the emissions and their images were smaller and balanced during the specific intermediate processes such as plant care and pesticide application. *Emission group 2:* We received a reversed image for lucerne when compared to the previous group. The emission values (calculated pro rata to 1 year) in the processes of preparation and harvest were smaller than the values derived during the specific intermediate processes (several mowing, rotation, windrowing, baling). The technological specificity of Lucerne could be the cause of this.



Emission group 1



Emission group 2

Figure 3-4. CO₂ equiv. emission profile of the process steps in the territorial approach (1 ha)

In Emission Group 1, the CO₂ equiv. [kg/ha] emissions ratio between soil preparation, harvest and intermediate processes is approx. 65–35%. In the Emission Group 2, this proportion was more balanced at approx. 55–45%.

In our models, the CO₂ equiv. [kg/ha] emissions were generally shared between the main operational and additional service steps versus road travel in the proportion of approx. 70-30%. It is interesting to compare the trend of the similarly examined CO₂ equiv. emissions to other agricultural land uses in the territorial approach. According to Polgár et al. (2018), in harvest technologies of short rotation energy plantations (SREP) of willow/poplar in the 3rd year cutting age, the contribution to CO₂ equiv. emission of the field operations was approx. 20–30%, while that of the road travel (transport) processes was approx. 70–80%. In the 3 ha> poplar and in the 5–10 ha poplar or willow stands we found that 20–30% of fossil CO₂ equiv.

emissions are caused by the work in the felling area, while 70–80% are due to the loading, transport, and unloading of wood. In the technology processes of the 20 ha < poplar stand the distribution is 50–50% (Figure 5).

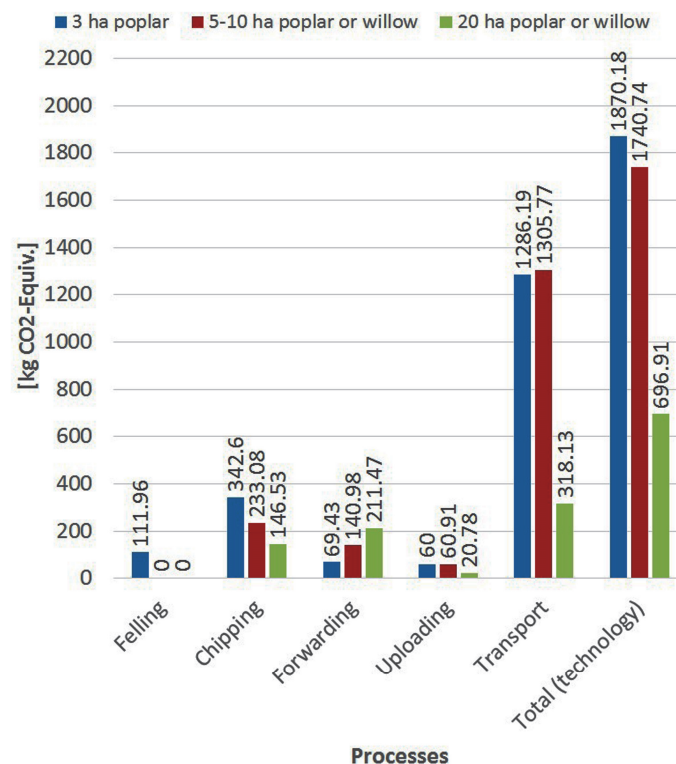


Figure 5. Contribution of processes in short rotation energy plantations to CO₂ equiv. emissions in fossil dimension of carbon footprint (Polgár et al. 2018)

Expressed as physical indicators in the case of arable cultivated plants (344.5–544.06 kg) in the territorial approach, we observed approx. CO₂ equiv. emissions that were two-to-three times smaller than in the case of SREP (697–1870 kg) (note: CO₂ equiv. [kg/ha] emission is counted only from fuel usage; the CO₂ equiv. emissions inherent in producing these is not included) (Polgár et al. 2018).

4 DISCUSSION AND CONCLUSION

Question: How do these technologies relate to other biomass producing systems?

We compared the values received in the examination of the cultivation technologies to the values typical for SREP displayed above. To obtain a nuanced interpretation of the results, we applied the quantitative approach in addition to the territorial approach. The figure below compare the global warming potential values (GWP 100 years) (Figure 6).

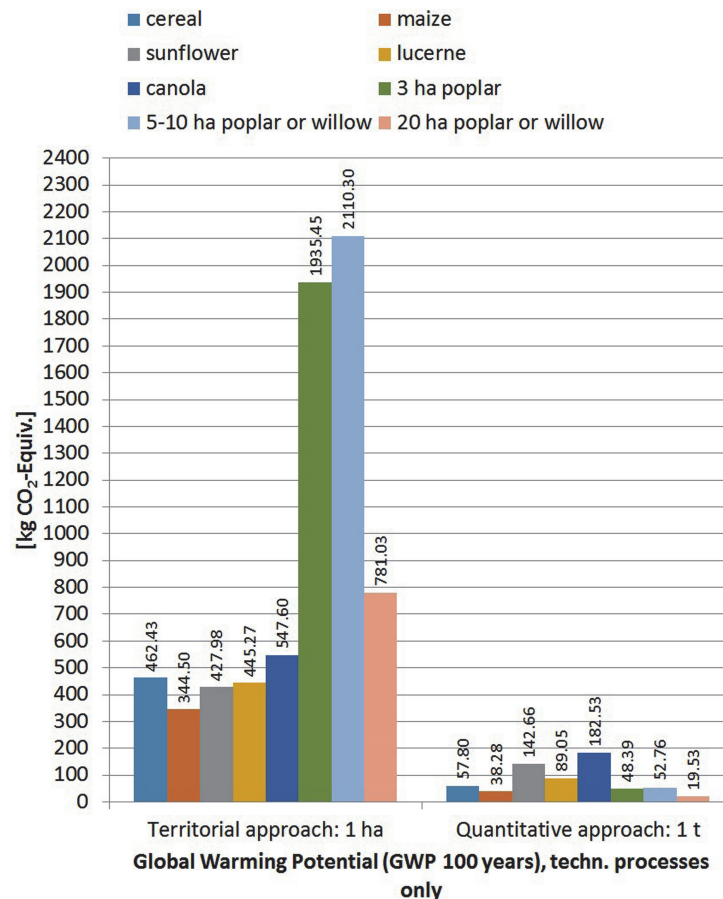


Figure 6. Global warming potential values (GWP 100 year) in territorial (1 ha) and quantitative (1 t) approach in the harvest operations systems of the examined cultivated plants and the short rotation energy plantings in the 3rd cutting age

The CO₂ equiv. emission profile analysis results were reflected in the territorial approach (1 ha). The analysis trends were valid in all additional impact categories; that is, they displayed 2–3 times smaller environmental impact values in cultivated plants than SREP.

Question: What is the expected carbon footprint of cultivation technology (in the quantitative approach, 1 t)?

When the carbon footprint contributions of cultivation technologies are expressed as percentages, we received the following increasing technological ranking in the quantitative approach (1 t): maize (8%) – cereals (11%) – lucerne (17%) – sunflower (28%) – canola (36%). With the same expressed in measurement units [kg CO₂-equiv./ha], we received the following increasing technological ranking: maize (38.28 kg) – cereals (57.8 kg) – lucerne (89.05 kg) – sunflower (142.66 kg) – canola (182.53 kg).

We must emphasize that we achieved a more nuanced understanding in the territorial approach because cereals and maize presented almost equal, lucerne almost two times, sunflower almost three times, canola almost four times the carbon footprint values [kg CO₂-equiv.] of the similar indicator of the SREP. This can be explained by the atmospheric emissions resulting from the larger quantities of fossil fuel produced and used in the quantitative approach (Table 3).

Table 3. Environmental impacts of examined systems based on CML2001 (Jan. 2016) assessment method in the quantitative approach (1 t)

Environmental impact category (CML2001 – Jan 2016)	Cultivated plant				Short rotation energy plantation			
	Cereals	Maize	Sunflower	Lucerne	Canola	3 ha poplar	5–10 ha poplar or willow	20 ha poplar or willow
Abiotic Depletion (ADP elements) [kg Sb eq.]	6.71E-06	4.44E-06	1.66E-05	1.03E-05	2.12E-05	2.87E-06	2.63E-06	1.08E-06
Abiotic Depletion (ADP fossil) [MJ]	8.63E+02	5.70E+02	2.13E+03	1.32E+03	2.72E+03	7.71E+02	7.01E+02	2.89E+02
Acidification Potential (AP) [kg SO ₂ eq.]	0.03	0.02	0.08	0.05	0.10	0.05	0.04	0.02
Eutrophication Potential (EP) [kg Phosphate eq.]	0.01	0.00	0.01	0.01	0.02	0.01	0.01	0.01
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	0.36	0.24	0.89	0.55	1.13	0.50	0.46	0.19
Global Warming Potential (GWP 100 years) [kg CO ₂ eq.]	63.13	41.78	155.67	97.20	199.00	1525.08	1543.39	1514.53
Global Warming Potential, excl biogenic carbon (GWP 100 years) [kg CO ₂ eq.]	66.88	44.33	165.00	103.00	211.00	1528.63	1546.73	1515.88
Global Warming Potential (GWP 100 years), techn. processes only [kg CO ₂ eq.] / 1 t	57.80	38.28	142.66	89.05	182.53	48.39	52.76	19.53

By comparing arable crop production values and SREP values, we highlight the experiences resulting from the quantitative approach (1 t) in a few significant impact categories below:

- Regarding the abiotic depletion (ADP fossil) category, the same trends were observable as those in the global warming potential (GWP 100 years) impact category in the comparison process
- When comparing the acidification potential (AP) values of arable crop production with similar SREP values, we must note that cereals and maize show nearly 0.6-times, lucerne almost equal, sunflower nearly 1.5-times, and rapeseed nearly double the values of SREP. The reason could be the ammonia and NO_x emissions from fertilisation.
- Comparing the eutrophication potential (EP) values of arable crop production with the similar values of SREP, the values of cereals and maize are 0.33 times, the value of lucerne is almost 0.5 times, the value of sunflower is almost equal, and the value of canola is almost 1.5 times the values of the indicator of SREP. This can be due to differing rates of fertiliser and herbicide usage.
- Comparing the freshwater aquatic ecotoxicity pot. (FAETP) values of arable crop production with the similar values of SREP, cereals and maize values are 0.75 times, the lucerne value is almost equal, the sunflower value is almost 1.5 times, and the canola value is almost double the indicator SREP values. The reason for this could be differing rates of lubricant, fertiliser, and herbicide usage.

The research outcomes are only comparable with other LCA studies cases involving the same functional unit and system boundaries. A better understanding of environmental impacts can be improved by the extension of system boundaries and inventories, and the involvement of further primary and secondary processes.

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