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Ecological evaluation of biogas from catch crops with Sustainable Process Index (SPI)

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Abstract

Background: Ever increasing global population requires to find additional options or increase the efficiency of food and feed supply to fulfil its dietary needs. In agricultural sector, competing situations with energy supply occur and ask for more sustainable solutions in an ethically correct manner.

Methods: The Sustainable Process Index (SPI) provides a powerful method for an ecological evaluation of various processes. The comparison of partial ecological pressures allows to identify main spots of ecological pressure and provides a base for an integrated discussion about ecological improvement.

Results: The results show scenarios about different options to change typical agricultural business as usual (BAU) successions. Mulching and fermentation of catch crops show high grades of reduction potential of the ecological footprint evaluated with the SPI method. A comparison to natural gas equivalent shows the direct potential to improve agricultural farming towards higher sustainability. The highest reduction of the ecological footprint can be between 56% in case of summer catch crops with wheat as a main crop and 59% in case of winter catch crops with maize as a main crop in comparison to the BAU scenario without catch crops.

Conclusions: Besides energy generation, the use of catch crops instead of main crops in biogas plants has several additional ecological benefits. Leaving main crops untouched for food and feed purposes, the additional seeding of catch crops after the harvest of main crops reduces the risk of erosion and nitrate leaching as well reduce the application of mineral fertiliser. Additionally, soil humus content improves due to the application of fermentation residues to the fields.

Background

In many places, agricultural energy generation from biomass can result in competing situations between food, feed and energy. Cropping systems focussing on one or two main crops in order to achieve maximum yields can lead to heavy pressures on soil and environment and as a consequence endanger future food and feed supply. Current challenges in bio-resource management are to:

- Sustain intact arable land and food production [1]
- Guarantee economic feasibility
- Further develop farming processes so that they can bring increased economic and ecological benefits [2]

Agriculture is limited in providing comparably small amounts of renewable resources to cover total energy needs. However, the local availability and the variety of options to provide food and energy resources can be better organised. Flexible solutions, in some cases decentralised systems, can contribute to both, food and energy security.

Hence, agriculture finds itself in the middle of a competition to provide biomass for materials and energy purposes and food. A confrontation with this challenge is needed followed by actions to handle this concurrency situation. Alternative options must be found by all actors involved in farming processes.

Fields do not have to be necessarily harnessed for the purpose of energy generation only. Agricultural areas can also be used more efficiently. Soil cultivation in a temperate climate where usually only one catch crop per year is harvested does not necessarily mean that additional biomass cultivation must be supplemented

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horizontally (meaning that additional agricultural land is needed). Biomass generation can also be increased on the same area where usually just one main crop is planted per year. Even more, a horizontal exploitation of land should be avoided because the availability of intact soil for agriculture is limited.

However, additional cropping potential can be developed when some farming techniques and sequences are changed [3]. One example which could play a role in this debate is shown in the work where summer and winter catch crops are sown in field experiments during the projects Syn-Energy I [4] and II [5]. These experiments showed that an additional competition on arable land could be avoided because energy crops were grown in intermediate periods between successive plantings of main crops. Also, the yields of the main crops remained constant and the import of additional fertiliser could be decreased. Catch crops were used to produce biogas. Different options to use this biogas for energy purposes were discussed. An ecological evaluation of the overall process was conducted including the cultivation of main and catch crops along with biogas production and its utilisation.

Methods

Sustainable Process Index

Available ecological evaluation methods are manifold and can show different aspects of ecological pressure, impact and cost [6]. The scenarios were evaluated according to the environmental compatibility with the Sustainable Process Index (SPI) [7]. The SPI is defined according to the following two principles of sustainability to embed man-made activities sustainably into nature as follows [8]:

1. Human activities must not alter long-term storage compartments of global material cycles in quality as well as in quantity. If this principle is not adhered to, resources will be depleted and substances accumulated in the ecosphere, overstraining the natural cycles.
2. Flows to local ecosphere have to be kept within the qualitative and quantitative range of natural variations in environmental compartments. If such flows exceed the amount a compartment can integrate, the accumulating substances will alter the compartment. This alteration can lead to a local environment that is no longer able to sustain flora and fauna.

The output of the evaluation is an aggregated number which can be taken to identify the ecological pressure of human activities. The larger this number is, the higher the environmental impact. Detailed mathematical calculation implementing these assumptions can be found in literature [9]. The final result is an aggregated number of ecological footprint in square metres evaluated with SPI. In this study, the term "ecological footprint" will always stand for the evaluation of the ecological footprint with SPI.

The practical evaluation of the agricultural processes was carried out with the freely available online tool SPIonWeb [10]. This tool consists of a graphical user interface and a database including typical life cycle data to create specific process cycles [11].

Goal and scope of the study

In the projects Syn-Energy I and II data, field experiments were undertaken during the years 2009 and 2015 to collect data about yields, emissions and erosion rates. These field experiments were conducted in different scenarios of soil cultivation, cultivation techniques and types of field crops. In field experiments, one focus laid on winter catch crops harvested in spring before the cultivation of maize and soy bean as main crops. In the practical testing, wheat was sown as a common main crop before the growing of summer catch crops. To create comparable scenarios for the SPI evaluation, some assumptions were made. There are two main crops which are typically sown in Austria. One of these crops was wheat *(Triticum)* with an average yield of 6 t/ha with 88% DM (dry matter) content. Another crop was silage of maize *(Zea mays)* with an average yield of 50 t/ha with 30% DM content. The crops were planted in succession with fallow land or catch crops. Summer catch crops were used in different amounts and compositions including seeds to grow different types of plants.[1] Summer catch crops are mainly grown in succession to cereals. As winter catch crops, other plants[2] were selected and harvested immediately before the cultivation of maize or soybean. These plants were selected according to their suitability for high methane yields. In Germany and Austria, average methane yields of catch crops can go up to more than 1600 m^3/ha. This experience can be learned from several studies [12].

The comparison of machinery includes use of different technologies like plough, cultivator, rotary harrow, mulcher and direct seeding machine. The time segments, when soil was cultivated for main crops with or without catch crops, kind of plant and technology used is given in Table 1. It includes dates of soil coverage, soil cultivation, and seeding and harvest of summer catch crop (s-cc) and winter wheat for the calculation of erosion with BoBB.[3] In cropping systems with ploughing, it is common to combine rotary harrow and seeding in one pass. Separation as indicated below was due to requirements of BoBB.

The sequences for main crop with or without winter catch crops (w-cc) cultivation, type of crops planted and

Table 1 Cultivation techniques and sequences using summer catch crops

Date	Without s-cc	s-cc mulched	s-cc harvested, ploughing for main Crop	s-cc harvested no ploughing
21 July	Winter wheat stubble	Winter wheat stubble	Cultivator/disc harrow	
22 July			Seeding s-cc	
29 July		Cultivator/disc harrow	s-cc	s-cc
30 July		Seeding s-cc		
16 September	Ploughing	s-cc		
15 October	Fallow		Harvest s-cc	
16 October	Rotary harrow	Ploughing		Cultivator/disc harrow
17 October	Fallow	Rotary harrow		Fallow
18 October	Seeding winter wheat			
20 July	Harvest winter wheat			

technology use, are shown in Table 2. It includes dates of soil cultivation, seeding and harvest of winter catch crop and maize for the calculation of erosion with BoBB [13].

For winter and summer catch crops, the yields varied from 2.5 up to 6 t DM/ha depending on the metabolism of respective catch crops seed mix, climate, soil, cultivation techniques and local weather conditions. For winter catch crops, the date of harvest is most decisive for achievable yields as well as the risk of lower yields for the succeeding main crop.

The data collected during the field experiments concerning yields, fertiliser demand, humus, soil quality, emission sources and sinks was needed for the ecological assessment using the online tool SPIonWeb. Scenarios were made for the main crops wheat and maize. As a

Table 2 Cultivation techniques and sequences using winter catch crops

Date	Without w-cc	w-cc mulched	w-cc harvested, ploughing	w-cc harvested, no ploughing	w-cc harvested, ploughing	w-cc harvested, no ploughing
04 October	Maize stubble	Maize stubble	Ploughing	Maize stubble	Ploughing	Maize stubble
05 October		Ploughing	Rotary harrow	Cultivator/disc harrow	Rotary harrow	Cultivator/disc harrow
06 October		Fallow	Seeding w -cc			
09 October		Seeding w-cc	w-cc	w-cc	w-cc	w-cc
10 October	Ploughing	w-cc				
10 April	Fallow	Cultivator/ disc harrow				
15 April	Rotary harrow	Fallow				
24 April	Fallow		Harvest w -cc			
25 April			Cultivator/disc harrow			
26 April	Seeding maize					
01 May	Maize	Maize	Maize	Maize	Harvest w -cc	
02 May					Cultivator/disc harrow	
03 May					Seeding maize	
30 September	Harvest maize					

reference scenario, a typical BAU (business as usual) case with fallow land between wheat and maize was taken. Two further scenarios were made, where on the same field main crops were succeeded with catch crops. One of these scenarios shows how much the ecological pressure changes when natural gas is substituted with biomethane produced from these catch crops. The other one shows differences when these catch crops are just left on the field for mulching without using them for fertilising. To get a better understanding of what happens when using main crops or residues from main crops for biomethane additionally, two variations of the BAU scenario were evaluated. An assumption indicates that a maximum of 20% of arable land could be taken for energy generation. This value was taken as a limiting factor for one of the variations [14]. In this context, the project team decided that this dedicated part of land could then be used for biomethane production substituting an equivalent amount of natural gas to fulfil the energy demand. For a better understanding of complex real world problems and for a consistent comparison, the LCA terminology was expanded to a mixed evaluation. Instead of a straight forward comparison of strictly separated processes, an evaluation of mixed processes derived from an observation of practical actions was evaluated.

The total agricultural production process cycles on the test areas from soil cultivation and seeding to harvest of the main crops, and catch crops were evaluated with Sustainable Process Index (SPI) which already has been successfully tested in different fields of application [15]. The data obtained from the project partners, including biogas potential, changes in humus system, erosion, N_2O (nitrous oxide), NH_3 (ammonia) emissions and NO_3 (nitrate) leachate, was utilised to ecologically evaluate catch cropping systems with SPI [16].

Results and discussion

Scenario generation

During the projects Syn-Energy I and II, possible contributions of catch crops were tested, and beneficial effects for soil, water, erosion and weed management could be measured [17]. On different test areas,[4] in Austria, different mixtures of catch crops were sown in the time gaps (fallow periods) between typical growing periods of two main crops: maize and wheat. Further processing of catch crops in bio-fermentation processes and the use of digestate as fertiliser reduces the amounts of conventionally used mineral fertilisers, particularly if legumes were integrated in catch crop mixtures.

The ecological evaluation of Syn-Energy II uses the following assumptions that derived from project results as well as experiences from other projects carried out by the authors:

- Winter wheat with summer catch crops and maize with winter catch crops: Each scenario considered two kinds of soil cultivation and harvesting methods and yields of main crops (winter wheat 5.3 t DM; maize 15 t DM) and catch crops (winter 4.5 t DM; summer 4.5 t DM).
- About 30% of biogas manure produced from winter-catch crop is used as fertiliser for the following main crop, whereas in the case of summer catch crop, up to 80% of biogas manure is used for the following main crop.
- It is assumed that summer catch crop with a minimum share of 50% legumes and 2 t of legume dry matter yield per hectare have a fixation performance of 70 kg N/ha, winter catch crops (e.g. forage rye with *trifolium incarnatum*) fix 20 kg N/ha.
- A reduction in the use of mineral nitrogen fertiliser can be reached due to a N-fixation of the legumes and a reduction of wash-out and emissions.
- Consequent catch cropping reduces weed burden whereby the use of herbicides is reduced by 20 to 50%.

The detailed deduction of these assumptions is out of the scope of this study and can be taken from the homepage of the Climate and Energy Fund of the Austrian government.

Figure 1 shows the assumed natural cycles with important emissions and interactions in the soil-water-air system (brown part, left side). Embedded in the natural cycles, the green part (right side) gives an overview of the anthropogenic agricultural process options considered in this study. In comparison to BAU cropping system, main crops are used to fulfil nutritious demands only. This study goes one step ahead. The main crops are still reserved for nutrition but supplemented with catch crops. The catch crops can be processed to biogas production process (including fermentation, combined heat and power (CHP) generation, biogas cleaning to biomethane and use of biomethane as fuel in biomethane fuelled tractors).

Side parameters and scenarios

It has been assumed that there are three main types of soil:

- Heavy soil: very compact, consists of clay and many other fine particles
- Medium soil: compound of clay, humus, sand and clastic sediments
- Light soil: mainly sand

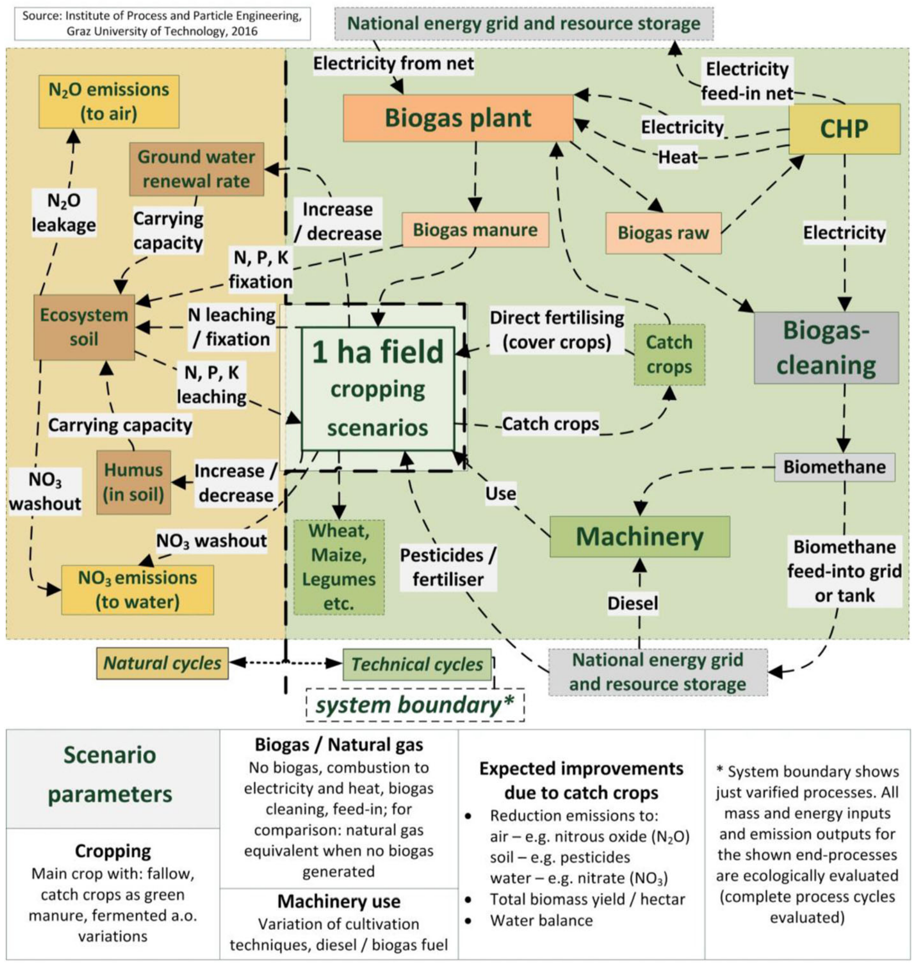

Fig. 1 Maximum cultivation, emission cycle and energy network of considered scenarios

Fuel consumption as well as nitrate leaching are dependent on the type of soil available for cultivation. In the current study, an average catch crop yield of 4.5 t DM (dry mass) was chosen. In the case of green manure, a catch crop yield of 2.5 t DM has been used and the catch crops were directly mulched into the ground to increase soil fertility. In the case of BAU (business as usual) scenario, there is a fallow period between two main cropping periods. Similarly, overall fuel consumption for each scenario has been calculated for cultivation in medium soil type. The use of heavy duty tractors (70 to 110 kW) and other machinery has been integrated into all processes.

The evaluated scenarios for the wheat production (System I) can be described as follows:

- Conventional (BAU): wheat followed by fallow land; 1260 m^3 natural gas equivalent
- Main crop wheat in succession with summer catch crops mulched as green manure for fertilisation; 1260 m^3 natural gas equivalent
- Main crop wheat in succession with summer catch crops harvested for production of 1260 m^3 biomethane; biogas manure applied to the field as fertiliser; ploughing, tractors fuelled with diesel (in Fig. 2) results of this scenario are presented)

The evaluated scenarios for the maize production (System II) can be described as follows:

- Conventional (BAU): 15 t DM maize per hectare followed by fallow land; 1260 m^3 natural gas equivalent
- Main crop maize in succession with winter catch crops mulched as green manure for fertilisation; 1260 m^3 natural gas equivalent
- Main crop maize in succession with winter catch crops harvested for production of 1260 m^3 biomethane and biogas manure returned to field as fertiliser; ploughing, chopper; tractors fuelled with diesel

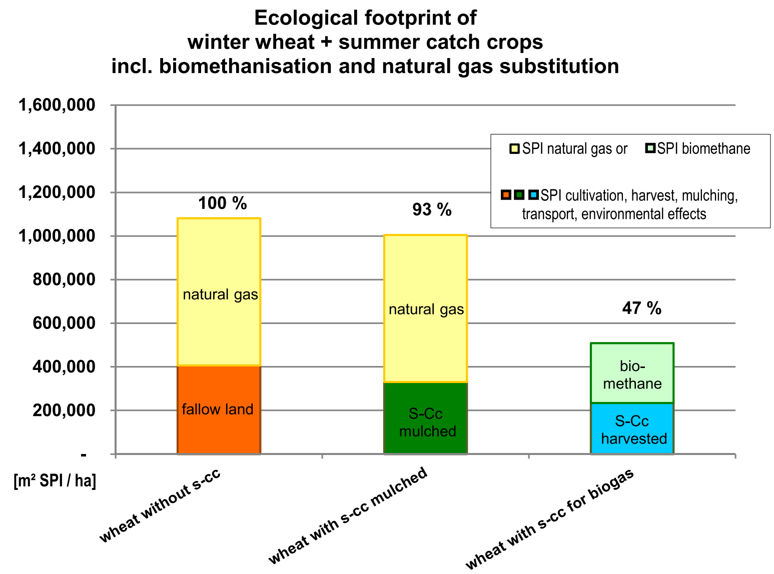

Fig. 2 System I: SPI scenarios—wheat as main crop and summer catch crops mulched or for biogas production per hectare

- Conventional (BAU) variation 1: maize followed by fallow land; 20% of arable land for 1260 m^3 biomethane production; 80% of arable land for food or fodder. This assumption equals to the use of the field for food and feeds production over 4 years and 1 year for energy production.
- Conventional (BAU) variation 2: grain maize or corn-cob-mix production followed by fallow land, maize straw used to produce 1260 m^3 biomethane

Biogas produced from biomass can be used in different processes:

- Combined heat and power for electricity and heat production
- Biogas cleaning for fuel purposes (e.g. tractors)
- Feed-in to gas grid

System I

The ecological footprint alters depending on the final product and its usage. The assumed parameters and data for the ecological evaluation for System I are given in Tables 3 and 4.

In the scenarios V0 (fallow land between the main crop periods) and V1 (catch crops as direct fertiliser remaining on field), for the comparison, an equivalent of natural gas was added to provide a complete comparison with the biogas produced in the other scenarios. The fuel consumption, based on soil type (light, medium, heavy), in tractors from 70 to 110 kW was taken from the KTBL database [18]. The yield for wheat was constantly assumed with 6 t DM/ha for all scenarios. For V0, V1 and V2 (ploughing of soil and harvesting of catch crops for biogas production), one ploughing a year was assumed. In V3, conserving soil cultivation was assumed because weed pressure can be reduced. In V4, agricultural machinery is driven with biomethane from catch crops. The lifecycle can so be closed for fuel use in agriculture.

System II

The system with maize as a main crop (see Tables 5 and 6) was not only compared with the scenarios having fallow land and applying mulching of the catch crops but also with biogas production from maize and maize straw. Additionally, scenario V5 shows how the self-sufficiency to run the biogas plant and biogas cleaning with electricity and heat from a biogas block power plant influences the size of the ecological footprint. For the biogas production from maize, a maximum of 20% of the field can be used for energy purposes. Thus, from one representative hectare, just 20% of the yield was used for biogas production and the rest for animal fodder. Considering the competition for land, it was assumed that maize used for energy must be compensated by an import of an equivalent amount of fodder. For a simplification, a purchase of silo-maize was assumed resulting in an ecological footprint evaluation of 1.2 ha maize.

The biogas production, as well as the specific process steps and the evaluated ecological footprint are shown in Figs. 2 and 3.

System I

The description of the scenario results of system I can be seen in Fig. 2. In system I, wheat was set as a main

Table 3 System I: Ecological footprint (SPI [m^2/ha]) of s-cc (for biogas or mulched) with wheat as the main crop

	V0 without cc	V1 cc mulched	V2 cc biogas, ploughing	V3 cc biogas no ploughing	V4 cc biogas no ploughing, biomethane
Wheat (t/ha) with 12% residual moisture	6.0	6.0	6.0	6.0	6.0
Cc yield (t DM/ha)	0	2.5	4.5	4.5	4.5
Wheat, technique, fuel, maintenance resource	244,000	208,000	185,000	160,000	150,000
Cc technique. fuel	0	3,000	28,000	29,000	29,000
NO_3, H_2O, erosion, humus	162,000	119,000	21,000	19,000	19,000
Sum wheat/biomass production	406,000	330,000	234,000	209,000	198,000
SPI change in relation to V0 (%)	100	81	58	51	49
SPI change in relation to V1 (%)		100	71	63	60
Biomethane/natural gas (m^3)	1260	1260	1260	1260	1260
Natural gas demand or biogas fermentation, cleaning, compression (m^2 SPI/ha)	675,000	675,000	275,000	275,000	275,000
SPI Sum incl. natural gas substitution or biomethane supply	1,081,000	1,005,000	509,000	484,000	473,000
SPI change in relation to V0 (%)	100	93	47	45	44
SPI change in relation to V1 (%)		100	51	48	47

crop alternated with summer catch crop for biogas production. The ecological footprint was calculated for 1 ha agricultural land containing medium emission values of all three classes of soil (heavy, medium and light). Additional use of catch crops has an additional potential to produce biomass and hence energy regionally. This option can reduce energy dependencies on fossil fuels as well as the ecological footprint. The use of catch crops as manure instead of biogas production can reduce the ecological footprint by 7% compared to the conventional

Table 4 System I: case study based extra input parameters for s-cc (for biogas or mulched) with wheat as the main crop

	V0 without cc	V1 cc mulched	V2 cc biogas, ploughing	V3 cc biogas no ploughing	V4 cc biogas no ploughing, biomethane
Wheat tonne per hectare with 12% residual moisture	6.0	6.0	6.0	6.0	6.0
Cc (t DM/ha)	0	2.5	4.5	4.5	4.5
Diesel consumption wheat (L/ha)	71	71	71	36	36
Diesel consumption Cc (L/ha)	0	6	60	42	42
Mineral N-fertiliser wheat (kg N/ha)	150	120	100	100	100
N_2-fixation summer catch crop	0	30	50	50	50
Biogas digestate with 8% DM-content (t/ha)	0	0	18	18	18
P-fertiliser SP (kg/ha)	8.0	8.0	8.0	8.0	8.0
K- fertiliser SP (kg/ha)	9.0	9.0	9.0	9.0	9.0
Ca-fertiliser SP (kg/ha)	31.3	31.3	31.3	31.3	31.3
Herbicide MCPA SP (kg/ha)	0.14	0.14	0.14	0.14	0.14
Herbicide Mecoprop-P SP (kg/ha)	0.11	0.11	0.11	0.11	0.11
Fungicide Tebuconazole SP (kg/ha)	0.01	0.01	0.01	0.01	0.01
Fungicide Tebuconazole SP (kg/ha)	0.03	0.03	0.03	0.03	0.03
Molluscicide Methiocarb SP (kg/ha)	0.01	0.01	0.01	0.01	0.01
NO_3-emissions (kg/ha)	34	32	25	25	25
N_2O emissions (kg/ha)	4.3	5.3	4.6	4.6	4.6
Erosion (t/ha)	1.3	1	1	0.4	0.4
Humus (kg C/ha)	64	236	369	369	369
Other basic parameters	Additional data and information about material and technology use: http://spionweb.tugraz.at/				

Table 5 System II: ecological footprint (SPI [m^2/ha]) of w-cc (for biogas or mulched) with maize as main crop and biogas production from maize on 20% of field; and from maize straw

	V0 without cc	V1 cc mulched	V2 cc biogas, ploughing	V3 cc biogas no ploughing	V4 cc biogas no ploughing, biomethane	V5 ZF cc biogas no ploughing, 100% self-sufficiency	Biogas maize on 20% field	Biogas from 75% maize straw (4.5 t DM/ha)
Maize (50 or 15 t DM/ha)	Silo-maize 100% used as fodder						Silo-maize 80% fodder, 20% biogas	9 t DM CCM as fodder
Import/purchase fodder	–	–	–	–	–	–	3 t DM maize silage	–
ZF Biomassebildung (t TS/ha)	0	2.5	4.5	4.5	4.5	4.5	0	0
Wheat, technique, fuel, maintenance resource	387,000	365,000	346,000	335,000	312,000	312,000	464,000	387,000
Cc technique, fuel	0	3,000	20,000	21,000	21,000	21,000	0	21,000
NO3, H2O, erosion, humus	293,000	172,000	104,000	101,000	101,000	101,000	351,000	293,000
SPI sum maize/biomass production	679,000	541,000	470,000	457,000	434,000	434,000	815,000	700,000
SPI change in relation to V0 (%)	100	80	69	67	64	64	120	103
SPI change in relation to V1 (%)		100	87	84	80	80	151	129
Biomethane/natural gas (m^3)	1260	1260	1260	1260	1260	1260	1260	1260
Natural gas need/biogasfermentation, cleaning, compression	675,000	675,000	280,000	280,000	280,000	118,000	280,000	323,000
SPI sum incl. natural gassubstitution	1,354,000	1,216,000	750,000	737,000	714,000	552,000	1,095,000	1,023,000
SPI change in relation to V0 (%)	100	90	55	54	53	41	81	76
SPI change in relation to V1 (%)		100	62	61	59	45	90	84

Table 6 System II: input parameters of w-cc with maize as main crop

	V0 without cc	V1 cc mulched	V2 cc biogas, ploughing	V3 cc biogas no ploughing	V4 cc biogas no ploughing, biomethane	V5 cc biogas no ploughing 100% self-sufficiency	Biogas maize on 20% field	Biogas from 75% maize-straw (4.5 t DM/ha)
Maize (50 or 15 t DM/ha)	Silo-maize 100% as fodder						Silo-maize: 80% fodder, 20% biogas	9 t DM CCM as fodder
Import/purchase fodder							3 t DM Maize silage	
Cc (t DM/ha)	0	2.5	4.5	4.5	4.5	4.5	0	0
Diesel consumption wheat (L/ha)	105	105	105	86	86	105	105	105
Diesel consumption Cc (L/ha)	0	6	60	42	42	0	0	0
Mineral N-fertiliser wheat (kg N/ha)	190	170	155	155	155	155	190	190
N_2-fixation summer catch crop	0	20	35	35	35	0	0	35
Biogas digestate with 8% DM-content (t/ha)	0	0	18	18	18	18	18	18
P-fertiliser SP (kg/ha)	24	24	24	24	24	24	24	24
K- fertiliser SP (kg/ha)	139	139	139	139	139	139	139	139
Ca-fertiliser SP (kg/ha)	126	126	126	126	126	126	126	126
Herbicide Phenmediapham SP (kg/ha)	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Herbicide Terbuthylazin SP (kg/ha)	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62
Herbicide Pyridate SP (kg/ha)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
NO_3-emissions (kg/ha)	28	26	21	21	21	21	28	28
N_2O emissions (kg/ha)	4.4	4.9	4.5	4.5	4.5	4.5	4.4	4.4
Erosion (t/ha)	3.7	1.5	1.6	0.8	0.8	0.8	3.7	3.7
Humus (kg C/ha)	−169	97	199	199	199	199	−169	−169
Other basic parameters	Additional data and information about material and technology use: www.spionweb.tugraz.at							

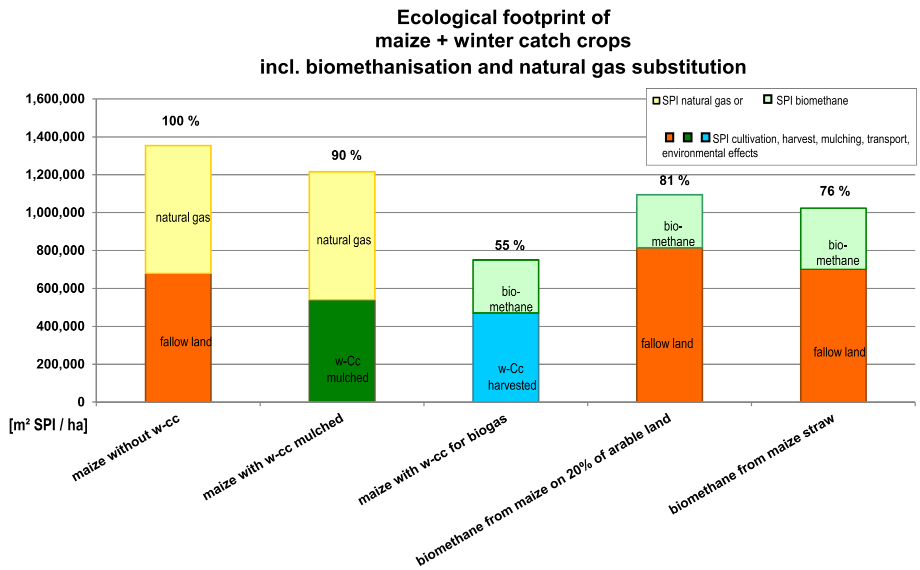

Fig. 3 System II: SPI scenarios—maize as main crop and winter catch crops for biogas production per ha cultivation area

process. Similarly, the use of catch crops for biogas production can reduce ecological pressure up to 53% compared to conventional processes.

The ecological footprint for the evaluation of cultivation, harvest, mulching and transport without considering the substitution of natural gas with biomethane can be reduced by 19% for mulched catch crops compared to the conventional scenario without catch crops (V0). The SPI can be reduced by 42% for catch crops which were harvested, fermented and then mulched (instead of transported) compared to scenario V0. The comparison of cropping system (excluding the ecological pressure of natural gas and biogas production) shows that the scenarios without catch crops (just fallow land) have a 20 to 35% higher SPI already than in scenario V0.

System II

Figure 3 shows results of system II. The use of catch crops as green manure can reduce the ecological footprint by 10% compared to conventional farming without catch crops. Ecological pressure due to maize cropping can be reduced by 45% with catch crops used for biogas production compared to the conventional scenario without catch crops (V0). The SPI for cultivation, harvest, mulching and transport of catch crops without considering the substitution of natural gas with biomethane can be 20% lower than scenario V0. For harvested, fermented and mulched catch crops, the SPI can be 31% lower than in scenario V0.

In the scenario where 20% of maize production on arable land is used for biogas fermentation, the total ecological footprint can be reduced by 19% compared to the conventional BAU scenario (maize without w-cc). If only straw of grain maize or corn-cob-mix is used for biomethane production, the ecological footprint is reduced by 24% compared to the conventional BAU scenario. It is assumed that providing maize for the fermentation process requires substitution of feed, e.g. by import, and therefore increases the ecological pressure on field by 20%. If only maize straw is used for biomethane production, it grows slightly by 3% because of harvesting field residues. The comparison of the cropping system (without the ecological impact of natural gas and biogas production) reveals that the scenarios without catch crops (just fallow land) have a 10 to 28% higher footprint already. The highest reductions of the ecological footprint can be between 56% (in case of V4 at s-cc/wheat) and 59% (in case of V5 at w-cc/maize) in comparison to scenario V0.

Conclusions

The substitution of fossil fuels with biogas from biomass from field without using the main crop for energy purposes can have several benefits. The generation of energy from catch crops means no additional competition for land use. This can be an opportunity to better guarantee food security, and energy can be provided from biomass on the same area where food and fodder are grown.

In scenarios with catch crops seeding, it was possible to reduce the amount of additional nitrogen fertilisers. Similarly, differences in cultivation techniques showed that erosion, humus, nitrous oxide emissions and nitrate leaching are important parameters to be considered in ecological footprint calculations. In all cases, there were ecological benefits when main crops were supplemented with additional biomass on field instead of leaving the land fallow. In this relation, the reduction of the ecological footprint was clearly higher when biomass was not just directly mulched but used for biogas. Evaluating the bigger context, the comparison of BAU, natural gas use and biogas from catch crops showed that reductions of the ecological footprint can reach 50% of the total footprint value.

Endnotes

[1]The following summer catch crops were chosen: Egyptian clover (*Trifolium alexandrinum*), sorghum (*Sorghum*), sunflower (*Helianthus annuus*), phacelia (*Phacelia*), mungo (*Guizotia abyssinica*), persian clover (*Trifolium resupinatum*), field mustard (*Sinapis arvensis*), oil radish (*Rhaphanus sativus* var. Oleiformis), lopsided oat (*Avena strigosa*), summer triticum (*Triticale*), buckwheat (*Fagopyrum*), broad bean (*Vicia faba*), sweet pea (*Lathyrus saltivus*)

[2]The following winter catch crops were chosen: Forage rye (*Secale cereale*), crimson clover (*Trifolium inkarnatum*), fodder pea (*Pisum arvense*/Sativum) and common vetch (*Vicia sativa*).

[3]Bodenerosion, Beratung, Berechnung; engl.: soil erosion, consulting, calculation; a tool to calculate soil erosion

[4]The test areas were Hasendorf/Leibnitz, Güssing, Ottsdorf, close to Thalheim/Wels, Pölla, close to Mank, Schönabrunn/Rohrau, close to Bruck/Leitha and Güssing.

Abbreviations

BAU: Business as usual; BoBB: Bodenerosion, Beratung, Berechnung (soil erosion, consulting, calculation), tool to calculate amounts of erosion from soil and phosphor flux to water; cc: Catch crop; CCM: Corn-cob-mix; ha: Hectare; kg/ha: Kilogramme per hectare; kg C/ha: Kilogramme carbon per hectare; kg N/ha: Kilogramme nitrogen per hectare; kW: Kilowatt; m^2 SPI/ha: Square metre ecological footprint per hectare, evaluated with Sustainable Process Index; m^3/ha: Cubic metre per hectare; s-cc: Summer catch crops; SPI m^2/ha or SPI (m^2/ha): Result of Sustainable Process Index in square metres SPI per hectare; SPI: Sustainable Process Index; t/ha: Tonne per hectare; t DM/ha: Tonne dry mass per hectare; t DM: Tonne dry mass; t: Tonne; w-cc: Winter catch crop

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Authors' contributions

The authors have contributed to the SynEnergy 2 project. SM, MS and KS have written, read and approved the manuscript.

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Competing interests

The authors declare that they have no competing interests.

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