Are catch crops sustainable for biogas production?

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Abstract Catch crops cultivated in autumn or over winter can be used as green manure, forage or co-substrate in biogas production. But which catch crops and catch crop mixtures are preferable, in terms of environmental and economic sustainability? We studied the life-cycle impacts and economic viability of four catch crop species and four catch crop mixtures under Swiss conditions. The catch crops proved efficient in eutrophication reduction, but were less sustainable in terms of global warming, non-renewable energy use, acidification and costs than silage maize. Considering the biogas potential, overwintering crops were more sustainable than autumnal crops. In summary, we conclude that catch crops for biogas production need to develop a certain yield and fulfill ecological functions in order to be sustainable, i.e. autumnal crops should be early-sown and grown with a low fertilizer input preferably, while overwintering crops are preferable.

Introduction

Policy is promoting renewable energy and the efficient utilization of renewable resources throughout Europe and adjacent countries in order to reduce the use of fossil energy and greenhouse gas emissions. Biogas production from biomass has thereby become a secondary field of income for European farmers over the last decade. Energy from biogas made up 7.7% of renewable energy production in 2008 in Germany [1]. This share is also due to the promotion of silage maize cultivation for biogas production, which is the main energy crop in Europe [2]. The production of energy plants worldwide has recently become questioned in relation to its competition with the production of foodstuffs. To avoid or confine this competition, the energy plant production would need to be carried out on non-agricultural land, or, if on agricultural land, as secondary production in periods outside of the best growing seasons [3].

Secondary crops are already partly used in agricultural bioenergy production [4, 5], also because they serve as additional co-substrates in the fermentation of agricultural wastes and energy crops. Secondary crops such as overwintering grass-clover mixtures are, however, often used as animal forage and the usage as energy biomass could therefore indirectly compete with human nutrition. Nevertheless, autumnal fallows are still a widely seen practice in Europe. Not only for soil regeneration or water saving purposes, but also due to additional costs for seeds and labor whilst no or little revenue allied with green manures. Secondary crops or catch crops therefore have a potential as supplementary energy biomass, generating direct revenue for the farmers and potentially fulfilling at the same time known ecological functions, such as reduction of nitrate leaching, erosion reduction, and carbon sequestration [6].

Sustainability of the major energy crops has been assessed, with varying results for the crops and energy products [7-9]. Whether catch crops for biogas production can be produced sustainably in terms of economic viability and environmental impacts is the key question of this study. The environmental sustainability is assessed by means of life cycle assessment. Our primary economical assumption is that catch crops producers will base their decisions on a fiscal weighing of the relative costs and benefits associated with each farming system, choosing a system that optimizes the ratio of the economic costs to the economic benefits. We aim at evaluating the sustainability and elaborating recommendations for the use and cultivation measures of catch crop production for energy purposes.

1 Materials and Methods

1.1 Life Cycle Inventories

In a first step, the system boundary was defined in agreement with the guidelines of ISO 14040 [10]. All measures related to the crop production of one hectare were considered from the harvest of the previous crop to the harvest of the examined crop. Farm infrastructure was only considered for the necessary production measures (machinery for soil tillage e.g.). Life cycle inventories for three groups of catch crops were established: green manure, autumnal and overwintering catch crops. Two crops were assessed as green manure, two mixtures and three crops as autumnal, not-overwintering catch crops, and two mixtures and one crop as overwintering catch crops (see Table 1). The crops and mixtures were chosen according to the prevalent use by farmers and potential use as co-substrate in biogas plants in Switzerland. Life cycle inventories comprised the growing period of the crops and all inputs that are necessary for producing the crop in this period, including seeds, fertilizer application, soil cultivation practices, plant protection, and harvesting measures (except for green manure, which stays on the field). The final products are silage bales from catch crop silage. This product was chosen due to its storability and sale potential. The emissions associated with the catch crop silage bale production were accounted.

For each crop, different cultivation scenarios were investigated. We considered mineral and organic (slurry) fertilization for all crops, and the cultivation without fertilization for some crops. Different fertilization intensities and associated yield variability were tested for all crops, between 20 and 80 kg of N, without addition of other nutrients. Furthermore, we varied the sowing dates and the harvesting intensity for some crops, i.e. crop inventories included early and late sowing dates and one to three harvesting measures. Yield data for the different catch crops were taken from [11] and [12]. The yields were adapted according to fertilization intensity and harvesting frequency, but were assumed to be independent of fertilizer type. Production measures were inventoried in agreement with Swiss practice in green manure and forage production [13]. For the overwintering crops and the autumnal crop mixtures, dry matter contents of 35% for silage production were assumed, whereas a lower dry matter content of 25% was assumed for the autumnal crops mustard, phacelia and sunflower. These crops are likely to reach a dry matter content lower than 30% despite wilting [14, 15].

In addition to the catch crop inventories, we established life cycle inventories for silage maize, a reference crop that is widely used as biogas plant. The examined catch crops were considered as preceding crops to silage maize and their environmental as well as economic performance was compared to silage maize production with preceding fallow. Production data for silage maize were taken from [16] and [13]. Silage maize was supposed to be fertilized with 110 kg of N, 95 kg P2O5, 35 kg Mg, yield 175 dt/ha and being ensiled with a dry matter content of 30%.

Field losses of dry matter due to silage production was accounted for with 7.5% for silage maize and 10% for all catch crops [17], which corresponds to good climatic conditions for the harvest of silage maize and intermediate conditions for the catch crop harvest. Biogas potentials for the different crops were taken from [18-21] and were 575 m^3 biogas per ton organic dry matter for ensiled maize, 558 m^3 for ensiled SM 106, 200 and 210, 585 m^3 for ensiled Italian ryegrass, 588 m^3 for ensiled SM 101, and 336 m^3 for ensiled sunflower. No reference for biogas potentials of mustard and phacelia was available, and thus we adjusted them with the potential of sunflower.

Tab.1: Catch crops and mixtures used in the ecological and economical sustainability assessment

Green manure crops	Autumnal catch crops	Overwintering catch crops
Sinapis alba (mustard)	SM101: *Avena sativa* (57%) *Pisum sativum* (23%) *Vicia sativa* (20%)	SM200: *Lolium multiflorum* (57%) *Trifolium pratense* (43%)
Phacelia tanacetifolia (phacelia)	SM106: *Lolium multiflorum westerwold.* (56%) *Trifolium alexandrinum* (28%) *Trifolium resupinatum* (17%)	SM210: *Lolium multiflorum* (33%) *Trifolium pratense* (33%) *Lolium multiflorum westerwold.* (20%) *Trifolium alexandrinum* (13%)
	Sinapis alba	*Lolium multiflorum (Ital. ryegrass)*
	Phacelia tanacetifolia	
	Sunflower	

SM = standard mixture. Numbers refer to seed mixture descriptions in Switzerland.

1.2 Assessment of environmental impacts and economy

Direct field emissions of the crops were calculated with the Swiss Agricultural Life Cycle Assessment (SALCA) model [22]. For the ecological sustainability assessment according to ISO 14040, several environmental mid-point impact categories were selected: the demand for non-renewable, i.e. fossil and nuclear energy, global warming potential over 100 years, nitrogen eutrophication, acidification, and aquatic ecotoxicity potential. The determination of the impacts was carried out according to the methods of the ecoinvent database [23], IPCC 2006 [24], EDIP2003 [25], and CML01 [26]. Methods with possibility for regional adaptations (eutrophication, acidification) were adapted within the SALCA methodology. Calculations of impacts were carried out with SimaPro (Version 7.2.3, PRé Consultants bv, Netherlands).

For the economic sustainability, our study focused on a cost-benefit analysis at the Swiss domestic farm household level, as an analysis of the cost effectiveness of silage maize and, additionally, catch crops or green manures. The primary aim was to gauge the economic efficiency [27]. This approach involved weighting the total expected costs against the total expected benefits of the examined catch crops and cultivation scenarios, with desirable options being those that offer the greatest benefits in excess of costs. The calculation of costs and benefits were conducted for a one hectare Swiss crop allotment (details see in [27]). All cost calculations deriving from labour units are based on empiric data [28, 29] and use an hourly farm wage rate of 28 Swiss Francs. The calculation of machinery costs is based on the machinery cost report 2010 [30]. All remaining prices, costs, and interest rates, are derived from domestic market rates in 2009 [31, 32].

1.3 Sustainability evaluation

After having assessed the environmental impacts and the economy, catch crops were evaluated according to their environmental impacts for two functional units, per area (hectare) and per m^3 potential biogas production, considering also the total biogas potential. The catch crops were evaluated in combination with the silage maize production in order to determine which catch crop and cultivation scenarios (fertilization and harvest intensity) increase the least or even reduce the environmental impacts and costs of silage maize production, while offering a good biogas potential. The reference system was silage maize with preceding fallow. A weighting procedure for the different environmental impacts was not performed.

2 Results

Catch crops for biogas production resulted in positive and negative environmental impacts. Cultivating catch crops before silage maize compared to fallow resulted in a reduction of nitrogen eutrophication, increased the bioenergy production and contributed to aquatic ecotoxicity potentials by a far lower level than silage maize, but also resulted in an increase in the global warming potential, the use of non-renewable energy, acidification, and costs (Table 2). Green manure reduced the nitrogen eutrophication potential on average by 27% in comparison to fallow, the autumnal crops reduced the potential on average by 20% and the overwintering crops by 25% (Table 2). Most effective in reducing the eutrophication were, besides the unfertilized scenarios, the scenarios of SM 101, SM 106 and sunflower being fertilized with 20-30 kg N (data not shown). While the production of green manure made up on average 14% of the use of fossil and nuclear energy needed for the production of silage maize, autumnal crops needed on average 29% of the non-renewable energy and the overwintering crops 41%. In return, autumnal crops added to the biogas production of silage maize on average 12.5% (from a range of 5-23%), while overwintering crops added on average 29.5% (18-45% possible). The production of green manure, autumnal and overwintering catch crops generated on average greenhouse gas (GHG) emissions of 0.5, 0.75, and 1.11 t CO2 equivalents which equal 19, 28, and 41 % of the GHG emissions from silage maize production. The acidification potential of green manure, autumnal and overwintering catch crops was 72, 160 and 282 m^2 of endangered ecosystem, equaling 16, 35 and 58% of the acidification of silage maize production. Producing green manure, autumnal or overwintering catch crops made up 7-11% of the aquatic ecotoxicity potential of silage maize. The total costs of producing green manure, autumnal crops and overwintering crops increased on average by 15, 30 and 46%, respectively, compared to silage maize alone (Table 2).

Depending on the functional unit being hectare or m^3 biogas potential, the classification of sustainable crops differed. When considering hectare, the preferential crops and cultivation procedures were the unfertilized SM 106, the mustard fertilized with 20 kg N and the overwintering crops with one harvest. When considering the biogas potential, the preferential crops were the SM 101, either unfertilized or fertilized with 30 kg N, and the overwintering Italian ryegrass with three harvests and 60-80 kg N applied (Fig. 1).

Tab2: Environmental impacts and economy of investigated catch crop systems, as preceding crops to silage maize (SM) in comparison to fallow. Shown are means and SD (in brackets)

Group	Crop system	Biogas production 1000 m^3/ha	GWP (t CO$_2$ eq./ha)	NRE (GJ eq./ha)	Acidification (m^2/ha)	Eutrophication kg N eq./ha	Aq. Ecotox. (kg 1,4-DB eq./ha)	Costs (CHF/ha)
Fallow	+SM	8.4	2.7 (0.7)	27.4 (8.1)	452 (194)	88 (33)	75 (26)	5212 (190)
Green manure	Mustard+SM		3.2 (0.6)	31.0 (6.5)	524 (197)	64 (23)	78 (19)	5929 (180)
	Phacelia+SM		3.2 (0.6)	31.2 (6.5)	523 (197)	64 (23)	78 (19)	6076 (156)
Autumnal crops	Mustard+SM	9.3 (0.3)	3.4 (0.7)	35.5 (7.4)	630 (237)	75 (24)	81 (18)	6741 (186)
	Phacelia+SM	9.1 (0.3)	3.5 (0.8)	35.5 (7.7)	649 (237)	80 (25)	82 (17)	6721 (170)
	SM 101+SM	9.8 (0.2)	3.2 (0.7)	34.5 (7.2)	551 (226)	64 (26)	94 (21)	6731 (111)
	SM 106+SM	9.7 (0.5)	3.5 (0.7)	35.6 (7.4)	628 (275)	68 (26)	81 (18)	6948 (379)
	Sunflower	9.4 (0.04)	3.2 (0.7)	35.4 (7.4)	604 (252)	64 (25)	81 (19)	6807 (67)
Overwinter. crops	Ital. Ryegrass +SM	11.2 (1.0)	3.8 (0.9)	39.1 (8.5)	736 (320)	66 (23)	82 (18)	7672 (815)
	SM 200+SM	10.6 (0.7)	3.9 (0.8)	38.5 (8.4)	733 (320)	67 (24)	83 (18)	7627 (789)
	SM 210+SM	10.8 (0.9)	3.8 (0.9)	38.6 (8.5)	733 (320)	67 (24)	82 (18)	7600 (834)

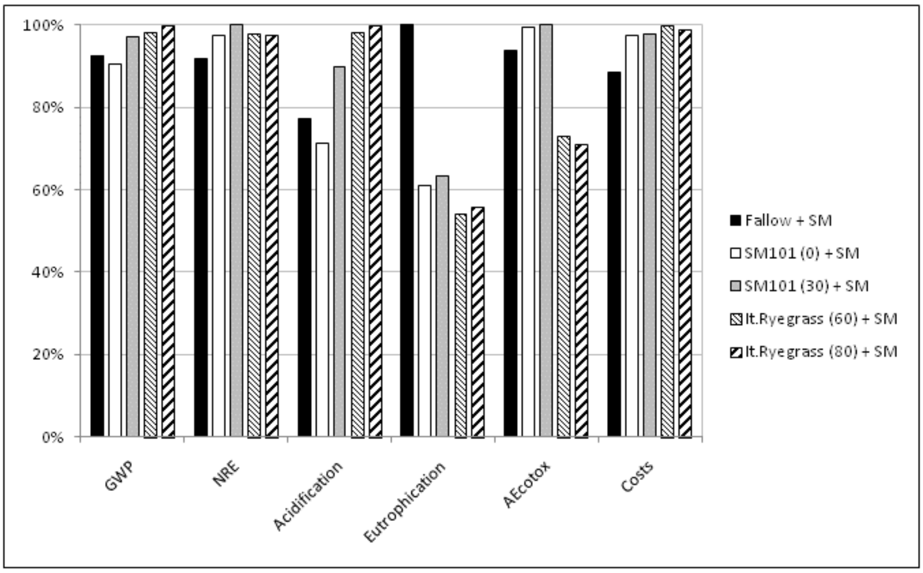

Fig.1: Percentages of environmental impacts and economy per m3 potential biogas production of silage maize with preceding fallow or catch crop. Shown are the most sustainable autumnal and overwintering catch crops SM 101 with no (0) and 30 kg N fertilized, and Italian ryegrass with 60 and 80 kg N

3 Discussion and conclusions

The assessment of the different environmental impacts and the economy has shown that catch crops are less efficient in biogas production than silage maize and are less sustainable than silage maize considering the use of non-renewable energy, the greenhouse gas emissions, the acidification potential and the costs. The positive aspects of the catch crop production are the reduction in eutrophication and the low ecotoxicity levels. Further known environmentally positive aspects of catch crops, which have not been considered, are erosion reduction, weed suppression, and carbon sequestration. These functions can still be fulfilled, even when the crops are harvested for biogas production.

When comparing silage maize and catch crops for biogas production, the difference in growing season has to be considered. Silage maize is a very productive crop, but it is not a short-term crop and could not be cultivated over winter. The catch crops therefore still have their eligibility as potential biogas providers.

Compared with autumnal crops, overwintering crops increase GHG emissions, the use of fossil and nuclear energy and the acidification potential more than the autumnal crops, but on the other hand they produce on average 2.5 times more biogas. Their advantage is also that they can be cut once more in spring before the seeding of the silage maize. The advantages of high productive winter crops have been recognized and are applied in Germany [15]. The disadvantages with highly productive winter crops such as winter rye are, that they can have a negative effect on the yield of the main crop, due to water deficiency or nutrient depletion [33]. Crop mixtures with legumes do not or only marginally reduce the yield of the following main crop.

As the recommendability of the catch crops depended on the functional unit considered, the decision is then a matter of priorities. Is the aim to have the least possible environmental impact per agricultural area, or is the aim to have a biogas substrate with a balance in biogas production and environmental impact per amount of biogas produced? As a low biogas yield of catch crops would result in a higher demand for agricultural area to produce more biogas, it would be reasonable to go for the second option. A high biogas yield of catch crops is then appreciable, as long as the catch crop production does not reduce the yield of the main crop, potentially a food crop, as mentioned above.

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