Environmental impacts of annual and perennial energy crops compared to a reference food crop rotation

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Abstract: *In the context of bioenergy promotion, the question rises whether the introduction of annual energy crops in crop rotations or the production of perennial energy crops are, compared to conventional food crops, adequate options not only for energy production but also to reduce the risk of nitrate leaching as well as to reduce fossil energy demand, greenhouse gas emissions and other environmental impacts.*

A reference crop rotation, an energy crop rotation and the perennial crops Miscanthus, willow (short rotation coppice) and permanent meadow are analysed. The crop rotations are balanced over 5 years and correspond to typical production scenarios for the investigated region. The life span of the perennial crops is 20 years and the results are converted to 5 years for comparison to the crop rotation scenarios. The system boundary includes all inputs and all activities on the fields from cultivation to transport of the harvested biomass to the farm. Fermented biogas substrate was recycled in the system and used as fertiliser as far as possible. The Swiss Agricultural Life Cycle Assessment methodology (SALCA) was used for the impact assessment.

Regarding the environmental impacts, the cultivation of perennial crops for energy production is a significant improvement compared to crop rotations. The energy crop rotation shows similar or lower impacts than the reference food crop rotation except for the eutrophication and acidification potential. To achieve a lower acidification and eutrophication potential, further optimisation in the selection and cultivation process of the crops (extensification of field processes, timing and formulation of fertilisers, crop rotation design) is needed, which would be applicable for food crops as well.

Disregarding the different utilisation of the products, the energy crops miscanthus and willow represent an ecological and economic alternative to conventional food production on arable land. The considered permanent meadow for energy production is a suboptimal option, because of low yields and the relatively high acidification potential. Considering the overall energy production, perennial crops show lower impacts than energy crop rotations. Political support of energy crops should therefore mainly focus on perennial energy crops.

Keywords: *energy crops, life cycle assessment, crop rotation, perennial crops,*

Introduction

The climate change and shortage of fossil energy resources leads governments to more and more support of bioenergy produced from agricultural biomass. Recently, the EU decided to raise the share of renewable energy to 20% of the total energy use in the year 2020. Earlier studies showed that energy production from agricultural biomass was not profitable in Germany (BMU 1999; Öko-Institut 2000; Maier et al. 1997). Nevertheless, energy crops could become competitive not only by considering tax reduction but also additional incomes thanks to possible contributions linked to ground water protection. In this case, energy crops are likely to replace conventional crops in some areas.

Agriculture as such is known to pollute the groundwater with nitrate. Our goal is to analyse whether the introduction of annual energy crops in crop rotations or the production of perennial energy crops are, besides reducing the fossil energy demand and the global warming potential, adequate options compared to conventional food crops to reduce the risk of nitrate leaching and other environmental impacts in southern Germany.

Methodology

Nemecek et al. (2005) showed that the comparison of farming systems only at the level of single crops may yield misleading results. The system boundaries are therefore extended to the whole crop rotation in the present study. We analysed the following crop production systems:

- Reference food crop rotation (5 years): winter wheat followed by turnip rape, corn followed by corn, summer barley, rapeseed followed by spontaneous greening.
- Energy crop rotation (5 years): triticale followed by turnip rape, silage corn followed by mustard, silage corn followed by mustard, summer barley, rapeseed followed by spontaneous greening.
- Perennial crops (20 years each): miscanthus; willow (short rotation coppice); permanent meadow.

The crop rotations are balanced over 5 years and correspond to typical production scenarios for the investigated region. The life span of the perennial crops is 20 years and the results are converted to 5 years for comparison.

The system encompasses the production of all inputs (mineral fertilisers, machines, pesticides) and all activities on the fields from cultivation to transport of the biomass to the farm. Application of farmyard manure was not included since most of the farms in the region do not have animal husbandry. The analysed systems differ in the type and quantity of fertilisers and pesticides applied, in the number of field operations and in yield (Table 1). The production inventories were developed specifically for the project by the local partners.

Table 1: Key characteristics of the five cropping systems analysed: Reference and energy crop rotation (CR), miscanthus, willow and permanent meadow (mean values per 5 years).

Mean values per 5 years	CR reference	CR energy	Miscanthus	Willow	Permanent Meadow
Average dry matter yield (kg)	34040	60530	78000	54500	40500
Mineral fertiliser (kg N)	665	468	213	94	150
Fermented biogas substrate (m3)	0	93	0	0	81
Pesticides (kg)	7.6	8.0	0.5	0.6	0.0
Number of pesticide applications	9.0	8.6	0.3	0.5	0.0
Number of other field operations	47.5	54.6	15.3	8.4	96.3

Various direct field emissions are estimated by means of models according to the SALCA method developed by Agroscope Reckenholz-Tänikon ART (as described in Nemecek et al. 2005):

- *Ammonia* (NH_3): the losses are estimated from the quantity of nitrogen applied and fixed emission factors according to Menzi et al. (1997). The emission factors range from 2% to 15% (released as N_2O) depending on the type of fertiliser used.
- *Nitrous oxide* (N_2O): direct and induced emissions are considered according to the IPCC method (see Schmid et al., 2000). Sources are the application of nitrogen fertiliser (factor 1.25% of N released as N_2O) and the incorporation of crop residues (1.25% of the N released as N_2O). Additionally, induced emissions from ammonia and nitrate losses are considered (1% for ammonia-N and 2.5% for nitrate-N).
- *Phosphorus*: three paths of P emissions to water are included: run-off (as phosphate), erosion to rivers (as phosphorus) and leaching to ground water (as phosphate). The model used is described in Prasuhn (2006).
- *Nitrate* (NO_3^-): nitrate leaching is estimated on a monthly basis by accounting for application of N fertiliser, N mineralisation in the soil and N-uptake by the crops according to the method described in Richner et al. (2006).
- *Heavy metal emissions* (Cd, Cr, Cu, Hg, Ni, Pb, Zn) are assessed by an input-output balance. The following inputs are considered: seed, fertilisers and pesticides. The outputs included are the harvested products, erosion and leaching. The model is described by Freiermuth (2006).

- Applications of *pesticide active ingredients* are considered as emissions into agricultural soil.

The LCA of crop rotations is performed with the SALCA-crop tool version 2.02 (Nemecek et al., 2005). The tool consists of modules programmed in Microsoft EXCEL® and a system implemented in the TEAM™ software (Version 4.0) from PriceWaterHouse Coopers/Ecobilan, Paris, France.

Nemecek et al. (2005) propose a selection of relevant impact categories and impact assessment methods for studies on agricultural systems. The following environmental impacts on mid-point level are considered here:

- Demand for non-renewable *energy resources* (oil, coal and lignite, natural gas and uranium), using the gross calorific value for fossil fuels according to Frischknecht et al. (2004b).
- *Global warming potential* over 100 years (according to IPCC, 2001).
- *Ozone formation* potential (according to the EDIP97 method, Hauschild and Wenzel, 1998)
- *Eutrophication* potential (impact of the losses of N and P to aquatic and terrestrial ecosystems, according to the EDIP97 method, Hauschild and Wenzel, 1998)
- *Acidification* potential (impact of acidifying substances released into ecosystems, according to the EDIP97 method, Hauschild and Wenzel, 1998)
- *Terrestrial ecotoxicity* potential (impact of toxic pollutants on terrestrial ecosystems, according to the EDIP97 method, Hauschild and Wenzel, 1998)
- *Aquatic ecotoxicity* potential (impact of toxic pollutants on aquatic ecosystems, according to the EDIP97 method, Hauschild and Wenzel, 1998)
- *Human toxicity* potential (impact of toxic pollutants on human health, according to the CML01 method, Guinée et al., 2001).

1 toxicity point represents 1000m3 soil, water or air respectively which is needed to reduce the concentration of a chemical below a harmful level.

Looking at the ground water protection potential and other land conservation and management functions, the environmental impacts per hectare are important. Otherwise, for the productive function (energy production from biomass) the results per organic dry matter are essential. Therefore, for decision making, the function of the agricultural production needs to be clearly addressed.

Results

The impact assessment shows major differences between both crop rotations and the perennial crops. An overview of the results is given in Table 2.

*Table 2: Environmental impacts of the energy crop rotation (CR) and the perennial crops in percent of the reference crop rotation per hectare times years (ha*a).*

Impact category with reference	unit/(ha*a)	CR reference	CR energy	Miscanthus	Willow	Permanent meadow
Energy demand [1]	MJ-eq	20751	107%	49% ++	27% ++	42% ++
Global warming pot. [2]	kg CO_2-eq	3616	95%	36% ++	19% ++	32% ++
Ozone formation [3]	kg ethylene-eq	0.714	125%-	53% ++	36% ++	52% ++
Acidification [3]	kg SO_2-eq	18.6	464% --	48% ++	20% ++	504% --
Eutrophication [3]	kg N-eq	68.8	158% -	44% ++	29% ++	72% ++
Terrestrial ecotox. [3]	Tox. points	362	79%	49% +	26% ++	8% ++
Aquatic ecotox. [3]	Tox. points	2767	96%	9% ++	7% ++	13% ++
Human toxicity [4]	Tox. points	57.6	102%	48% +	29% +	46% +
Direct nitrate leaching	kg N	45.8	122%	41% ++	26% ++	0% ++

Reading example: The energy demand of miscanthus equals only 49% of the food crop rotation and is therefore very favorable. (++ = very favourable, + = favourable, - = unfavourable, -- = very unfavourable).
[1] Frischknecht et al. 2004a, [2] IPCC 2001, [3] Hauschild & Wenzel 1998, [4] Guinée et al. 2001

Perennial crops compared to annual crops

Compared to crop rotations, perennial crops have a lower energy demand, global warming potential and ozone formation due to fewer field operations. Furthermore, they do not require as much mineral fertiliser as crop rotations. The production of mineral fertiliser needs a considerable quantity of non-renewable energy (Nemecek & Erzinger 2005) and generates emissions like carbon dioxide, ammonia and nitrous oxide. Miscanthus and willow show better results in acidification and eutrophication due to lower fertilisation and permanent soil coverage that reduces nitrate leaching (see Figure 2). The same is true for the eutrophication of permanent meadow, whereas its acidification potential is the highest together with the energy crop rotation. This is primarily due to emissions of ammonia caused by the application of fermented biogas substrate. No pesticide use in the permanent meadow and low pesticide use in willow and miscanthus result in a lower human- and ecotoxicology potential for these crops in comparison to that of crop rotations.

Energy crop rotation compared to food crop rotation

Comparing the energy crop rotation with the reference crop rotation, there is a higher impact on ozone formation due to more field operations (field cultivation, harvesting and transport of harvest). Intensive field operations combined with less input of mineral fertiliser result in a similar energy demand and global warming potential per hectare of the two crop rotations (see Figure 1). The acidification and eutrophication potentials of the energy crop rotation are higher because of the use of fermented biogas substrate as manure (see Figure 2). Both crop rotations show similar results per hectare in all other impact categories. Considering the functional unit kg organic dry matter (oDM), the energy crop rotation has a significantly lower energy demand and a lower eutrophication potential due to the higher yield.

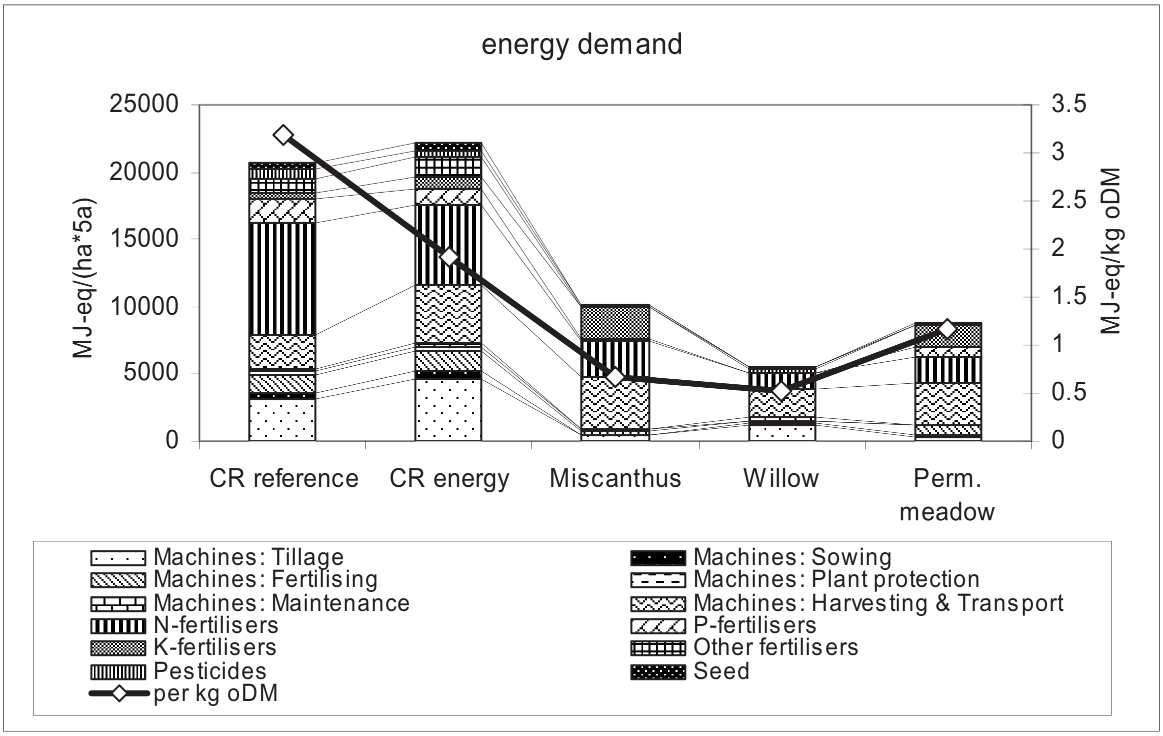

*Figure 1: Energy use per hectare and year (ha*a) and per dry matter unit (oDM) of the reference and energy crop rotation and the perennial crops miscanthus, willow and permanent meadow.*

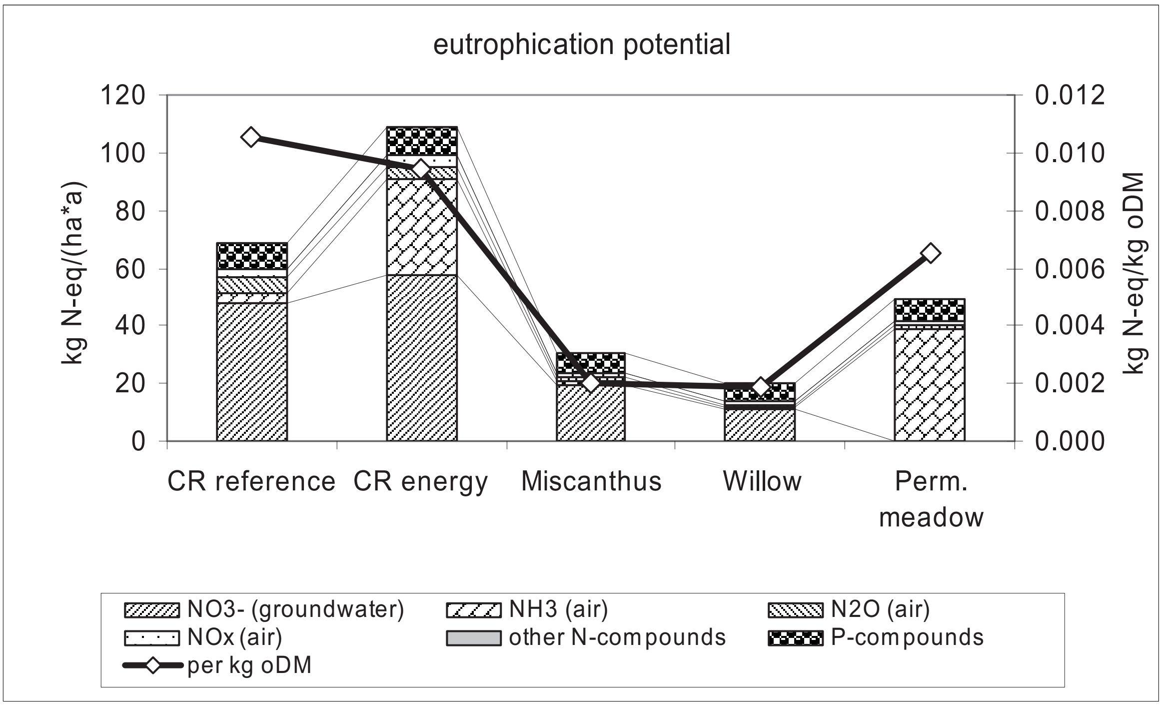

*Figure 2: Eutrophication potential per hectare and year (ha*a) and per unit of organic dry matter (oDM) of the five cropping systems.*

Economics

Figure 3 shows the gross margin of the five cropping systems. The governmental support of 45€ per hectare for energy crops is already included. The perennial crops miscanthus and willow show the best economic performance. Looking at the full costs, miscanthus also shows a very good performance whereas willow has higher expenses due to the necessary drying process. The definite profit for the farmer also depends on the actual price he obtains for the various energy crops and on the fix costs which strongly depend on the farming structure.

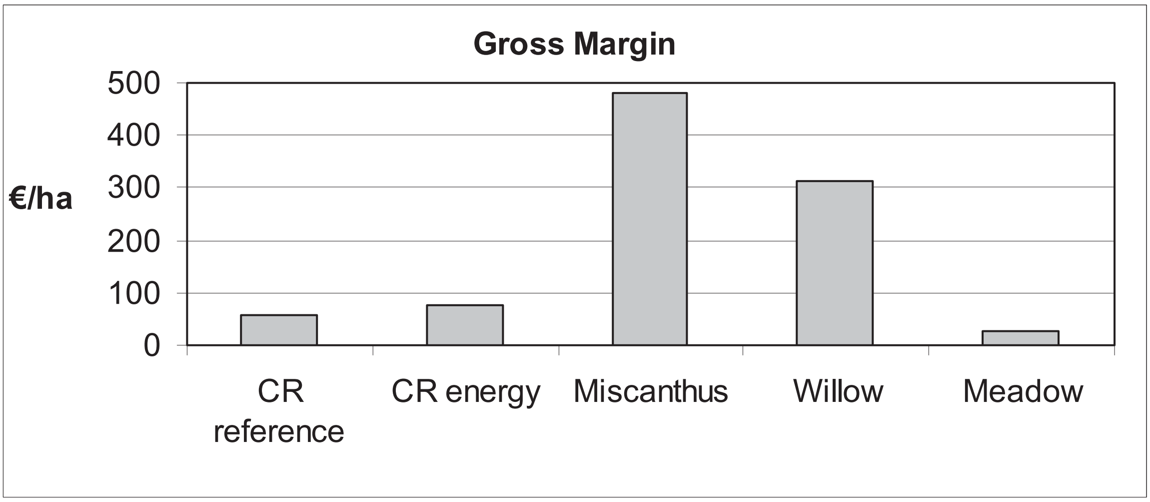

Figure 3: Gross margin of the five cropping systems in €/ha

Discussion and Conclusion

Regarding the environmental impacts, the cultivation of perennial crops for energy production is a significant improvement compared to crop rotations. The energy crop rotation shows similar or lower impacts compared to the reference crop rotation except for the eutrophication and acidification potential. Considering ground water protection, the cultivation of perennial crops for energy production is a distinct enhancement compared to crop rotations. Crop rotations need more intensive soil cultivation and fertilising that results in higher potentials of nitrate leaching. The analysed energy crop rotation is not suited for ground water protection due to high nitrate leaching. To achieve a lower eutrophication (and also acidification) potential, it would need further optimisation in the selection and cultivation process of the crops (extensification of field processes, timing and formulation of fertilisers, crop rotation design), which would be also applicable for food crops. LCA is a suitable instrument to assist in these optimization process.

Disregarding the different utilization of the products, the energy crops miscanthus and willow represent an ecological alternative to conventional food production on arable land. The considered permanent meadow for energy production is a suboptimal option because of low yields and the relatively high acidification potential. Considering as well the overall energy production, perennial crops show lower impacts than energy crop rotations. Political support of energy crops should therefore mainly focus on perennial energy crops.

The yield of energy crops is higher than the yield of crops for food production, since almost the whole plant is harvested. From a producer's point of view, energy crops are an interesting option bearing in mind the better environmental performances per kg product and by offering interesting opportunities for the diversification of farm products. This study shows that the agricultural function energy crop production can be ecologically competitive to food crop production.

Although there is governmental support for energy crops and the production of energy crops is quite profitable for the farmer, there is a certain economic risk. Nevertheless, depending on the value the farmer obtains for the biomass, energy crops can increase the farmer’s income. Furthermore, the opportunity to include energy crops into crop rotations leads to a diversification of crops. On the other hand, experience shows that investing in bioenergy always leads to a certain concentration of energy crops in the area near the conversation plant.

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