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ASSESSING THE ECOLOGICAL AND ECONOMIC SUSTAINABILITY OF ENERGY CROPS

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Abstract—The production and use of biomass for energy has both positive and negative impacts on the environment. The environmental impacts of energy crops should be clarified before political choices concerning energy crops are made. An important aid to policy-making would be a systematic methodology to assess the environmental sustainability of energy crops. So far, most studies on the environmental aspects of energy crops deal mainly with the energy production of the crops and the possible consequences for CO_2 mitigation. The Dutch Centre for Agriculture and Environment (CLM) has developed a systematic methodology to assess the ecological and socio-economic sustainability of biomass crops. The method is best described as a multicriteria analysis of process chains and is very much related to Life Cycle Assessment (LCA). Characteristics of our methodology are the use of:

- definition of functional units;
- analysis of the entire lifecycle;
- definition of yield levels and corresponding agricultural practices;
- analysis of both ecological and economic criteria;
- definition of reference systems;
- definition of procedures for normalisation and weighting.

CLM has applied the method to assess the sustainability of ten potentially interesting energy crops in four European regions. The results are used to outline the perspectives for large scale production of biomass crops with regard to the medium and long term land availability in Europe. For the crops considered, net energy budget ranges from 85 GJ net avoided fossil energy per ha for rape seed for fuel to 248 GJ net avoided fossil energy per ha for silage maize for electricity from gasification. The methodology of the tool and its results were discussed at the concerted action "Environmental aspects of biomass production and routes for European energy supply" (AIR3-94-2455), organised by CLM in 1996. Major conclusions of the research:

- Multicriteria analysis of process lifecycles is at present the best available option to assess the ecological and economical sustainability of energy crops. However, it is recognised that further research and development activities in the field of LCA are necessary.
- Use of crops for generation of electricity is preferred to use of crops for transport fuels since the latter score low on both ecological and socio-economical criteria.
- Large scale use and production of energy crops requires (a) choices and goals from agricultural, environmental, and energy policies, and (b) policy instruments for financial incentives e.g. with payments or with tax rebates, preferably per kilogram avoided CO_2 emission. © 1998 Elsevier Science Ltd. All rights reserved

Keywords—Biomass; sustainability; ecology; economy; energy crops; greenhouse gases; environment; chain analysis; LCA; land-use; incentives.

1. INTRODUCTION

Since the 1970s, biomass has attracted increasing interest in discussions on future European energy supply, both from policymakers and farmers. The Scientific Council for Government Policy in the Netherlands concluded that 40 to 100 million hectares in the European Unit (EU) may become available for purposes other than food crop production during the next decades.[1] Using part of this land for energy crops may satisfy a relevant part of the demand for energy in the EU, while at the same time reducing the emission of carbon dioxide (CO_2). For farmers, energy crops may be an interesting option because export subsidies on food crops are being cut back and the demand for agricultural products in the EU increases but slowly. Their interest has also been stimulated by the opportunity to grow non-food crops on set-aside land without losing the existing area grants.

However, the production and use of biomass for energy has both positive and negative impacts on the environment, as reported by several national and European environmental organisations.[2] The environmental impacts of energy crops should be clarified before political choices concerning energy crops are made. An important aid to policy-making would be a systematic methodology to assess the environmental sustainability of energy crops. So far, most studies on the environmental impact of energy crops deal mainly with the energy production of the crops and the possibilities for CO_2 reduction. Only a few comprehensive studies on environmental aspects of energy crops have been carried out. An important source of knowledge on the environmental impacts of biomass for energy is the work carried out by the Institute for Energy and Environmental Research (IFEU) in Germany.[3] In 1996 the Dutch Centre for Agriculture and Environment (CLM) organised the concerted action "Environmental aspects of biomass production and routes for European energy supply" (AIR3-94-2455),[4] the aim of which was to evaluate the state-of-the-art on the environmental impacts of biomass in the EU. Much attention was given to the method of Life Cycle Assessment (LCA). The methodology of LCA has been developed to gain insight in the environmental impacts of the production of a product during the whole life cycle or process chain (from "cradle to grave"). In the EU, (elements of) LCA has been used in various studies on energy crops in, for example France,[5] Germany,[3,6–9] Belgium,[10] and The Netherlands.[11–13]

CLM has developed a tool for assessing both the ecological and economic sustainability of energy crops: it provides the information needed to evaluate various options for achieving environmental goals and/or optimal land-use with energy crops. It may be used both at a regional and a national scale. The scientific basis of the tool includes a detailed description of the calculation method.[13] This paper first gives a brief description of the tool and then some examples of its use. Finally, we give the major conclusions and recommendations for further research that emerged from our work and from the concerted action.

2. METHODOLOGY

The aim of the tool is to compare the ecological and socio-economic sustainability of production and use of energy crops, both with other crops and with alternative crops, i.e. with non-energy crops and with fossil energy sources. Since energy crops may cause environmental impacts at local, regional and global levels, an assessment of all these impacts would be an important asset for the tool. In addition, it should account for the effects of each step in the lifecycle, i.e. from cultivation of the crop to its conversion into energy.

With this in mind CLM has developed a methodology which includes the following:

- definition of functional units;
- analysis of the entire lifecycle;
- definition of yield levels and corresponding agricultural practices;
- analysis of both ecological and economic criteria;
- definition of reference systems;
- definition of procedures for normalisation and weighting.

The methodology has much in common with environmental Life Cycle Assessment (LCA). The great advantage of LCA is that the various environmental effects are made explicit, facilitating rational debate and policy making. The CLM method differs from conventional LCA in that it focuses on agricultural production instead of industrial production. Land use is an important aspect of our methodology since (i) the availability of land for agriculture, including energy cropping, is limited, and (ii) land use determines largely the diffuse emissions of nutrients and pesticides. Another difference from LCA is that we included both ecological and economic criteria in the evaluation.

2.1. *Functional units*

A function unit describes the function that a product performs for society and defines the quantification of this function. Since the main functions of energy crops are energy production and land use, we defined two functional units:

- The equivalent of one gigajoule (GJ) of fossil energy. Using this functional unit, energy crops can be compared both with each other and with fossil fuels.
- The amount of agricultural product from one hectare in one year. With this functional unit we can compare energy crops with other crops.

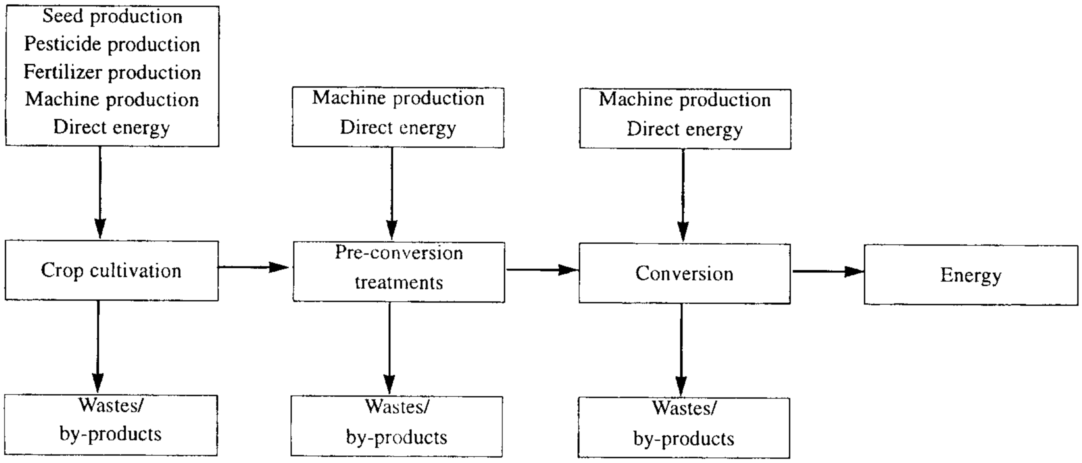

Fig. 1. Lifecycle of an energy crop.

2.2. *Lifecycle*

It is impossible to study a lifecycle completely: each input has its own life cycle, with new inputs, new lifecycles, etc. The same applies to outputs, such as wastes. Therefore it is necessary to define the lifecycle on which we focus. We set system borders of the lifecycle of an energy crop at the beginning of the cultivation period and at the energy output from the conversion process. Subsystems for waste and by-products are also included. Figure 1 shows the systems and subsystems considered in our method. Transport and storage play a role in each step between subsystems and secondary systems, but they are not stated in the figure.

Some crops may have a slightly different lifecycle because wastes and by-products are re-used. Study of the entire lifecycle is necessary for only some criteria, i.e. energy use, CO_2 emission, acidifying emissions and ozone-depleting emissions. The other criteria apply only to one subsystem, e.g. the emission of pesticides is only relevant to the crop cultivation system.

2.3. *Ecological and economic criteria*

After examining a number of environmental criteria, we selected 12 ecological and 3 economic criteria to be included in the tool. Criteria and their contents can be found in Table 1.

2.4. *Yield levels*

A distinction is made between actual and attainable practice over the entire lifecycle from cultivation to conversion. Actual practice reflects current cultivation practices and conversion processes. Attainable practice refers to the future, and assumes technical improvements for both cultivation practices and conversion processes. For the cultivation phase, attainable practice is estimated according to guidelines for good agricultural practice (GAP), assuming that environmental measures with low net costs will be taken. To estimate potential yield levels, we used the results of a simulation model designed by the Department of Theoretical Production Ecology at Wageningen Agricultural University.[16] The use of a model offers the opportunity to calculate a consistent set of yield levels for every crop in every region under consideration. The potential yields thus calculated are translated into realistic levels using yield factors, to allow for specific circumstances like weather conditions or differences in management skills. Table 2 gives agricultural input data as we used for crops in the Netherlands.

For the conversion process, it is assumed that energy efficiencies will be higher in attainable practice than in actual practice. Most data relating to conversion routes have been obtained from Biomass Technology Group of Twente University.[21]

2.5. *Reference systems*

An assessment method has been developed for each criterion. Energy crops may be compared with fossil energy sources using criteria 1, 2 and 3. All ecological and economic criteria may be used to compare energy crops with other energy crops or with non-energy crops. In general, energy crops will replace the crops with the lowest financial returns. At present, set-aside land has the lowest financial

Table 1. Ecological (nos. 1–12) and economic criteria (nos. 13–15)

Ecological criteria

1. Energy balance
   The net energy budget is calculated by subtracting the energy input from the energy output. This results in a net amount of fossil energy avoided, expressed in GJ per ha. All energy inputs and outputs are calculated on a primary basis, in terms of used or saved fossil energy in GJ per ha. Energy inputs in GJFOSSIL per ha are calculated for consecutive steps of the process lifecycle, from production of seed and plant-cuttings to the process energy needed for combustion. Energy output (in GJFOSSIL per ha) is calculated in terms of fossil energy saved, being the total energy output during combustion and the energy needed to produce a substitute for any by-products.
2. Emission of greenhouse gases
   The net emission of greenhouse gases avoided (tons of CO_2 per ha) is calculated by subtracting the N_2O-emissions (in terms of CO_2-equivalents) from the amount of saved CO_2. The net amount of saved CO_2 can be deduced from the energy balance by attaching a CO_2 emission factor to each fuel type in the energy balance. The emission of N_2O liberated by nitrification and dentrification during crop cultivation is expressed in terms of CO_2-equivalents. N_2O emission is calculated in two different ways: either by using the general Bouwman formula[14] and the available nitrogen required from fertilizer and manure or (preferably) by making a detailed division of the nitrogen surplus.
3. Emission of acidifying gases
   The emission of acidifying gases is calculated separately for ammonia (NH_3), sulphur dioxide (SO_2) and nitrogen oxides (NOx). SO_2 and NOx-emissions occur both during cultivation and conversion.
4. Emission of ozone depleting gases
   As CFC's and halons do not play an important role in energy cropping, only N_2O emissions are calculated for their contribution to ozone depletion.
5. Emissions of minerals to soil and water
   Mineral emissions consist of emissions to soil and water, acidification and N_2O emission. Emissions to the soil and to groundwater and surface waters account for the larger share. These emissions are calculated with a balance method: output minus the input gives the mineral surplus for nitrogen, phosphate and potassium. Ammonia volatilisation (see 3) is subtracted from the nitrogen surplus to give the 'remaining nitrogen surplus', as an indicator for emissions to soil and water. Ammonia volatilisation is calculated separately by multiplying the amounts of fertilisers and manures by their respective volatilisation factors.
6. Emission of pesticides
   The "environmental yardstick for pesticides", developed by CLM[15], plays a central role in providing scores to be added to the environmental burden of pesticide emissions. This yardstick assigns "environmental impact points" to each individual pesticide application; these points reflect the groundwater contamination and the risks to water and soil organisms. The amount of pesticides per group and the likely applications are estimated for each crop, and the damage by the applications is determined following a scale from 1 to 7. Scores are higher when the score on the yardstick is greater than those allowed by the Uniform Principles of the European Union allow for persistence, contamination of groundwater and acute toxicity to water organisms. For each group of pesticides the amount applied per hectare is multiplied by the score for damage. The group totals are then added up to produce a total score per hectare. Also the occurrence of indirect effects on other crops in the rotation is analysed.
7. Soil erosion
   The risk of erosion for each crop is assessed on the basis of soil cover by leaves, stems and roots, and by rainfall. Crop growth is divided into four stages. A crop-dependent value for soil cover and the amount of rainfall are determined for each stage. These values are multiplied and added up to give an amount of "harmful rainfall".
8. Ground water depletion
   The amount of groundwater depletion caused by crops correlates with the amounts of water use in their cultivation. Water use is calculated with the same model calculations used for estimated yield.
9. Use of resources
   Apart from the (reduced) use of energy, use of resources is not a dominant aspect in energy cropping. Use of iron can be assessed, but it is time-consuming. The CLM methodology relies on the use of phosphate and potash fertilizer as a criterion for the depletion of fertilizer ores.
10. Waste production and utilisation
    The utilisation of animal manures and wastes (e.g. polluted water) and the uptake of substances from polluted soils by energy crops is valued positively, especially when these pollutants can be destroyed or recycled. It is valued negatively if conversion ashes are not recycled in crop cultivation, but withdrawn from the mineral cycle instead. Also, wastes such as sugar beet tarra are valued negatively. Assessments are translated into points, weighted and added up.
11. Contribution to biodiversity
    Three criteria are used to assess the contribution of a crop to biodiversity:
    a. species diversity (preferably with Simpson's diversity index);
    b. number of threatened species;
    c. number of characteristic species (species which are characteristic for the region and which benefit the crop).
12. Contribution to landscape values
    We distinguish two criteria for the impacts of a certain crop on landscape values: changes in the variation in landscape structure and in the variety of colours. Crops that lead to a greater variation in structure will have a positive value, except when the introduction of that crop seriously affects the landscape type, e.g. by affecting the openness of the landscape. Crops having different colours from the existing crops, or which display a large range of colours, also receive a positive value. Both criteria are assessed on a scale of −, 0 and + and combined to produce a weighted average.

Economic criteria

13. Cost price of energy produced
    The cost effectiveness of producing the final product is one of the main socio-economic criteria, since it determines the feasibility of production of energy from biomass. The energy cost price is calculated by adding the costs of three steps in the process lifecycle:
    1. The energy crop price at farm level: costs of cultivation, harvesting etc.
    2. Costs of transport, drying and off-farm storage.
    3. Costs of processing and conversion.
14. Costs of abated CO_2 emission
    A second important aim of the production and use of biomass for energy is to reduce the emission of greenhouse gases. The costs of reducing CO_2 emissions indicate progress towards reaching this second aim. These costs enable us to compare the cost effectiveness of different energy crop with various other options to reduce CO_2 emissions. To calculate the costs of the CO_2 emissions avoided, the net CO_2 reduction (see 2) is divided by extra costs of biomass energy. To calculate the extra costs, the costs of production of the reference fossil energy source are subtracted from the costs of the energy product price of the energy crop.
15. Employment creation per hectare
    An important argument for potential investments in energy crops is the assumed positive effect on employment, although a large labour requirement is a positive asset only if the labour is remunerated. In our assessment the labour requirement of energy crops is compared with the labour requirement of the reference system.

Table 2. Agricultural input data for crops in the Netherlands[17–20]

Crop kg N/ha	Nitrogen input kg	Pesticide use kg active ingredient/ha	Yield ton dm/ha
Rape seed	249	1.3	5.3
Sugar beet	290	3.8	14.7
Winter wheat	320	4.2	10.0
Silage maize	389	2.6	14.8
Hemp	136	1.0	10.7
Miscanthus	105	1.6	8.1
Poplar	99	0.4	7.0
Willow	116	0.4	7.8
Grass fallow	40	0	0

return, followed by cereals. Therefore, we used both fallow grassland and cereals as a reference crop.

2.6. *Normalisation and weighting*

To facilitate direct comparison of results, scores can be "normalised", i.e. translated into the same form of measurement. A simple form of normalisation is used: all scores are translated into a figure between 0 and 10, with 0 being a very bad score and 10 being a very good score. The scale is calibrated at two points:

- 5 denotes the score of the reference fallow grass crop. There is no such score for the economic criteria, i.e. the cost price of energy produced and the costs of reduced CO_2-emissions. Instead, we assumed that a score of 5 would be equal to 100% of the market value and to 50 ECU per ton of CO_2 production avoided respectively.
- 0 or 10 is determined by the most extreme results of one of the crops in actual practice.

As a last step, the normalised scores can be weighted and then the weighted average score calculated for each crop. The use of weighting factors helps to make the relative importance of the different criteria more explicit. It cannot replace the evaluation of scores for separate criteria, but it can help to combine these evaluations into an overall assessment. Our weighting factors are made up from three elements for each criterion: general relevance, the potential contribution of energy crops and the reliability of the assessment. After multiplying the scores by their corresponding weighting factor, the weighted average score per crop can be calculated. Table 3 gives the weighting scores that have been used for the assessment for the Netherlands.

We do not pretend that this methodology results in an objective assessment, as it contains subjective and normative elements, for instance in the choice, implementation and weighting criteria and in the definition of agricultural practice. With this methodology we try to make an explicit assessment of sustainability, in order to lay the basis for a rational debate on sustainability of energy crops.

3. RESULTS

3.1. *The Netherlands*

The tool has initially been used to assess the sustainability of potentially interesting energy crops in North Netherlands. The crops included were oil seed rape, sugar beet, winter wheat processed to liquid transport fuels, and silage maize, hemp, miscanthus, poplar and willow used to generate electricity using various conversion routes. A set-aside area grant of 500 ECU is taken into account for all crops. It should be stressed that there is some uncertainty in several input data and calculation procedures. Table 4 shows the results of all assessments per criterion for actual practice in the North Netherlands.

Some important features of the ecological assessments are:

- The net energy budget ranges from 85 GJ net fossil energy avoided per ha for rape seed for fuel, to 248 GJ net fossil energy avoided per ha for silage maize for electricity from gasification.
- Rape, sugar beet and winter wheat for liquid fuels score low, especially with respect to energy production and abated CO_2-emission. In addition, each crop also receives low scores for several other ecological criteria, such as mineral emissions (all four), pesticides (wheat) and erosion (sugar beet). When expressed per GJ, scores on the criteria are very bad in comparison with those of "solid fuel crops".

Table 3. Weighting factors used to weigh normalised scores for the Netherlands

Issue Criterion	Energy Net budget	Greenhouse Net av. em.	Acidification Net em.	Ozone depletion N_2O em.	Minerals Min. surpl.	Pesticides Total Score	Erosion Harmf. rainf.	Water use Crop evap.	Resources Fert. use	Waste Waste pr ut	Biodiversity Av. score	Landscape Av. score	Energy price Rel. price	Cost av. CO_2 Costs av. CO_2	Employment Empl. cult.
total	1.8	2.5	1.0	0.2	1.0	1.0	0.2	0.5	0.1	0.5	1.1	0.3	2.5	2.5	0.7

Table 4. Final assessments for all criteria for actual practice in North Netherlands

Route	Crop	Energy Net budget GJfoss./ha	Greenhouse Net av. em. ton CO_2/ha	Acidificat. Net em. kg SO_2/ha	Ozone depl. N_2O em. kg N_2O/ha	Minerals Min. surpl. kg N/ha	Pesticides Total Score points	Erosion Harmf. rainf. mm	Water use Crop evap. mm	Resources Fert. use kg K eq./ha	Waste Waste pr/ut points	Biodiv. Aver. score points	Landscape Aver. score points	Energy price Rel. price	Costs av. CO_2 Costs av. CO_2 ecu/ton CO_2	Employment Empl. cult. hrs/ha
Extr. CHP	Rape seed	85	5.3	13	4.1	124	4.5	303	211	0	1.1	0.7	1.0	241%	127	17
Distillat.	Sugar beet	89	7.6	−11	4.7	139	5.6	431	256	117	0.7	0.3	−0.7	320%	228	36
Dist. CHP	Winter wheat	124	8.6	0	5.2	158	13.2	301	216	0	1.2	1.1	0.7	169%	72	17
Dist. CHP	Sweet sorghum															
Gas./CHP	Silage maize	195	13.4	28	6.3	194	9.0	469	217	113	2.5	0.0	0.0	183%	104	10
Gas./CHP	Hemp	206	14.2	−3	1.9	57	1.5	471	221	168	1.5	0.4	0.0	148%	41	17
Gas./CHP	Miscanthus	153	10.7	−1	1.1	33	2.9	233	211	100	1.5	0.5	0.0	199%	85	9
Gas./CHP	Poplar	128	8.8	−3	1.2	36	0.9	299	173	95	1.5	0.3	−0.7	123%	20	6
Gas./CHP	Willow	143	9.8	−1	1.3	39	0.9	220	203	85	1.5	0.1	−0.7	139%	35	6
Gas.CHP	Eucalyptus															
Gas.	Silage maize	248	17.6	13	6.3	194	9.0	469	217	113	2.5	0.0	0.0	166%	60	10
Gas.	Hemp	181	13.7	−7	1.9	57	1.5	471	221	168	1.5	0.4	0.0	145%	38	17
Gas.	Miscanthus	134	10.3	−5	1.1	33	2.9	233	211	100	1.5	0.5	0.0	195%	81	9
Gas.	Poplar	118	8.9	−7	1.2	36	0.9	299	173	95	1.5	0.3	−0.7	115%	13	6
Gas.	Willow	131	9.9	−5	1.3	39	0.9	220	203	85	1.5	0.1	−0.7	129%	25	6
Gas.	Eucalyptus															
Co-firing	Silage maize	183	13.1	32	6.3	194	9.0	469	217	113	0.0	0.0	0.0	123%	28	10
Co-firing	Hemp	133	10.4	7	1.9	57	1.5	471	221	168	−1.0	0.4	0.0	102%	2	17
Co-firing	Miscanthus	99	7.8	6	1.1	33	2.9	233	211	100	−1.0	0.5	0.0	153%	58	9
Co-firing	Poplar	87	6.8	2	1.2	36	0.9	299	173	95	−1.0	0.3	−0.7	79%	−23	6
Co-firing	Willow	97	7.6	5	1.3	39	0.9	220	203	85	−1.0	0.1	−0.7	90%	−11	6
Co-firing	Eucalyptus															
	Grass fallow	−5	−0.8	5	1.3	50	0.0	128	258	0	0.0	0.4	0.0			8

- Silage maize and hemp, both used in electricity routes, have the highest energy and greenhouse budgets. However, maize scores badly for the other criteria although hemp scores well. In the final weighted average score, hemp comes out as one of the best options for energy cropping.
- The other crops for electricity routes are perennial crops: miscanthus, poplar and willow. For poplar, net energy production and reduction of greenhouse gas emissions is moderate, while willow and miscanthus score reasonably well on these criteria. The scores on nearly all other ecological criteria are reasonably good.

Some important features of the economic assessment are:

- The cost price of liquid fuels extracted or distilled from rape seed, winter wheat and sugar beet (0.60–0.80 ECU per litre) is considerably higher than the fossil fuel price (0.20–0.30 ECU per litre).
- For electricity, conversion routes using poplar and willow are in general the cheapest. Prices are from 0.04 to 0.08 ECU per kWhe using fallow grass as reference, and are comparable with the expected market price of electricity (0.05 ECU per kWhe). This means that with an area payment of 500 ECU these crops could be economically feasible without CO_2 levy or premium for CO_2 reduction. The use of hemp, silage maize and miscanthus is slightly more expensive, with electricity prices of 0.05–0.09 ECU per kWhe for hemp and 0.06–0.13 ECU per kWhe for silage maize and miscanthus.
- With respect to the costs of CO_2 reduction, conversion routes producing electricity using poplar and willow are generally the cheapest, with cost prices from below zero to a maximum of 35 ECU per ton of CO_2 avoided. The cost price of CO_2 reduction with hemp is slightly higher: 2–41 ECU per ton, depending on the conversion route. Costs of CO_2 reduction for liquid fuels from rape seed, winter wheat and sugar beet are considerably higher: from 72 ECU per ton of CO_2 to more than 200 ECU per ton of CO_2.
- Sugar beet has the highest labour requirement, followed by rape seed, hemp and winter wheat. These crops are the most interesting for employment creation, providing the labour is paid. The labour requirement per hectare for willow is even less than for temporary set-aside. To meet the labour requirement of one full time labourer a farm specialising in willow will need a total area of 300 hectares.
- Introduction of willow, poplar and miscanthus with the aim to create on-farm employment, is only attractive in areas where there are no alternative crops, or where the alternative would be abandonment and marginalization.

3.2. *Examples for other regions*

Use of the tool is not restricted to the Netherlands. To demonstrate this, we extended the assessment to three other regions in Europe: Hessen (Germany), East Anglia (United Kingdom) and South Portugal. In addition to the crops examined for the Netherlands, we included sweet sorghum and eucalyptus in the assessment. In South Portugal, the relevance of the criteria erosion and ground water depletion is much higher than in the Netherlands. We adjusted the weighting factors accordingly. For the other regions the Dutch weighting factors were used. The available information only permitted an assessment of the ecological criteria and it must be stressed that many input data have a Dutch bias. The results of this assessment are shown for illustrative purposes only and should not be considered as absolute figures. Figure 2 shows the net CO_2 emission per hectare for the various crops in the four regions.

The main results of the assessment are:

- The net production of energy and reduction of greenhouse gases tend to increase with higher crop yields, as do the economic efficiencies. In contrast, scores for many other ecological criteria are influenced negatively by higher yield levels.
- Annual crops show better yields in the northern regions, whereas in Portugal perennial crops tend to produce better yields.
- Electricity routes appear to have much better net energy budgets than liquid fuel routes under the same conditions. Of the electricity routes, gasification combined with CHP gives the best results (around 200 GJ per ha in actual practice). For the northern regions, net budgets are highest for maize and hemp. For South Portugal, all energy

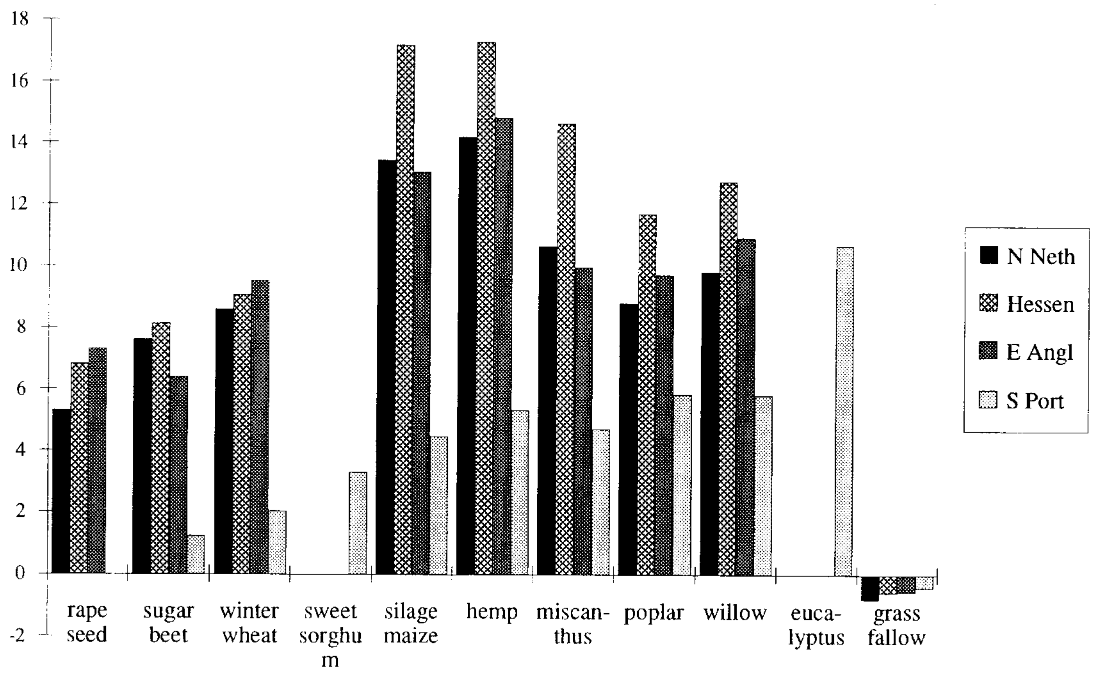

Fig. 2. Net emission of greenhouse gases in tons of CO_2-equivalent per ha.

and CO_2 budgets are low or very low under actual practice, but under attainable practice hemp and perennials achieve high energy budgets. Eucalyptus even generates over 400 GJ per ha, but has a very negative score for ground water depletion.

- In the northern regions, the weighted average of ecological criteria for all crops and routes are higher than for fallow grass. However, several crops and routes score worse under actual practice in South Portugal.
- The differences between the three northern regions are generally small, but in terms of actual practice they differ substantially from South Portugal.
- Several crops in South Portugal score reasonably well (miscanthus, poplar and willow), but eucalyptus scores much better for everything except ground water depletion. Eucalyptus has an extremely high evaporation: more than 50% higher than any other crop. Cultivation of eucalyptus may contribute to severe problems of ground water depletion, and should therefore be restricted to those areas where water availability and ground water depletion is not a problem.

The tool has also been used to assess what role biomass can play in the energy supply of the European Union. For this purpose the availability of land for energy crops was explored by confronting the areas that may become available with possible new land claims. An extrapolation of present trends shows that, without major policy changes, between 15 and 21 million ha of agricultural land may become available in the EU12 for use during the next decade. Energy production is surely not the only alternative use for the available land, as other land claims, e.g. extensification, nature development, and new outlets, may require 2–43 million ha of land. We estimated the maximum contribution of energy crops to the European energy supply at 8%. However, the contribution will be substantially lower if alternative forms of land-use are favoured.

With the present energy prices large scale production and use of energy crops would require financial support, either through area payments, tax rebates, subsidies for energy production or payments for CO_2 abatement. An area payment of 500 ECU per ha would make energy production with co-firing from willow and poplar feasible.

3.3. *Sensitivity analysis*

Analysis was made of the sensitivity of the results to changes in yield levels, efficiencies and emission factors, and in calculation factors for normalisation and weighting.

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Recalculation with both higher and lower yield levels shows that relative results do not appear to be very sensitive to this. With regard to weighting factors, it was found that if we increase the importance of emissions (acidification, minerals, pesticides), all crops score worse, with the scores for wheat and maize falling the most. If the importance of biodiversity and landscape is accentuated, the weighted average scores for most crops fall, but those of rape seed and winter wheat improve.

4. DISCUSSION

The methodology that we have developed is still in need of further refinement. We outline some points that may need attention in future work. The major comments and suggestions that came up during the concerted action have been included in the discussion.

- The results that have been obtained are not absolute figures. Owing to a lack of relevant input data for the assessment in regions outside the Netherlands, we had to use many Dutch data for these calculations. Furthermore, input data may change rapidly due to efficiency improvements in the techniques used for cultivation and conversion.
- In our methodology, we express subjective criteria, such as biodiversity and landscape values, in "hard" figures. However, both criteria have a strong dependence on human perception. For instance, in the Netherlands a landscape with blooming oil seed rape is considered as very attractive, whereas in the United Kingdom this is absolutely not the case. Hence our hard figures for landscape values may appear to be a false certainty. Our reason for doing this is that the translation of a qualitative judgement into a quantitative one will make these differences in perception clear and explicit, allowing discussion to take place.
- An important element in the final assessment is the process of normalisation and weighting. We adopted a simple form of normalisation. More elaborate methods would calculate the contribution of the crop to either the total impact in the region or the necessary reduction of the impact. Subjectivity in weighting procedures may be reduced by including panels of scientists or relevant social parties to assess weighting factors.
- The set of criteria to be used for the assessment is certainly not restricted to those proposed by us. Other ecological criteria that might be of interest are soil fertility and structure, particularly changes in the humus balances, and emission of local air pollutants. Economic criteria that could be added are effect on governments finance and macro economic effects.
- The availability of input data needed for the application of the tool is in many cases insufficient. This implies that our results should be interpreted with care, especially those for the regions outside the Netherlands. More research is needed to generate data, both from simulation models and from field experiments.
- Finally, the economic evaluation could be extended to other possible benefits of energy crops, e.g. green soil clean-up, the protection of groundwater quality and erosion control.

5. CONCLUSIONS AND RECOMMENDATIONS

The major conclusions and recommendations relating to the methodology of the tool may be formulated as follows:

- The methodology to judge the criteria on energy production, emission of greenhouse gases, emission of ozone depleting gases, emission of acidifying gases, emission of nutrients to soil and water and emission of pesticides does enable a good evaluation of energy crops for these criteria. This means that for these criteria the methodology is ready for wider application and that they may be built in LCA procedures involving energy crops.
- The criteria soil erosion, ground water depletion, use of resources, waste production and utilization, contribution to biodiversity and contribution to landscape values need further refinement.

Based on the results obtained with the tool developed by CLM, the following conclusions and recommendations for the production and use of energy crops in the EU may be drawn:

- In northern European regions, annual crops for electricity routes such as hemp deserve higher priority in research and policy, both from an environmental and an economic point of view:

- —they can be incorporated in arable rotations much more easily than perennial crops;
- —arable farmers have more experience with annual crops than with perennial crops;
- —initial investments are not as high as for perennial crops;
- —actual set-aside regulations offers better perspectives for annual energy crops than for perennial crops.

- Perennial crops for electricity routes offer better perspectives than crops for transport fuels and should therefore receive more attention from research and policy. Eucalyptus may be an interesting crop in South Portugal and comparable regions. However, eucalyptus should only be cultivated in those areas where availability of water is not a problem.

Since relatively little experience is obtained with perennial crops for energy production, more work is required to study their improvement potential.

The concerted action "Environmental aspects of biomass production and routes for European energy supply" (AIR3-94-2455) led to several suggestions for further research on the environmental impact of biomass for energy. In line with them are the following conclusions and recommendations of our work:

- Multicriteria analysis of process lifecycles is at present the best available option for assessing the ecological and economic sustainability of energy crops. However, it is recognised that further research and development activities in the field of LCA are necessary.
- There is a growing need for research on the effects and potentials of different policy measures to stimulate the production and use of biomass for energy. Stimulating energy crops requires clear choices and goals from agricultural, environmental and energy policies as well as policy instruments for financial incentives. For example, a premium per unit of abated emission of greenhouse gases may be an ideal instrument to stimulate the cultivation of energy crops.

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