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Life Cycle Analysis of field production of fibre hemp, the effect of production practices on environmental impacts

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Summary

Life Cycle Assessment (LCA) was used to assess the environmental impacts of field production of fibre hemp and seven other crops in France. The production of 1 ha of hemp yielded a eutrophication potential of 20.5 kg PO_4-equivalents, a global warming potential of 2330 kg CO_2-equivalents, an acidification potential of 9.8 kg SO_2-equivalents, a terrestrial ecotoxicity potential of 2.3 kg 1,4-dichlorobenzene-equivalents, an energy use of 11.4 GJ, and a land use of 1.02 ha.year. A comparison of hemp (low impacts), wheat (intermediate impacts) and sugar beet (high impacts) revealed that the crops were similar for the relative contributions of emitted substances and resources used to impacts, and for the relative contribution of processes to impacts. A reduction of the impacts of hemp production should focus on eutrophication, and consider the reduction of climate change, acidification and energy use as secondary objectives. Given this objective, the overall environmental effect of the substitution of mineral fertiliser by pig slurry is negative. The introduction of reduced tillage is of interest, as it decreases energy use, acidification and climate change. Measures leading to a reduction in NO_3 leaching are highly interesting, as they strongly decrease eutrophication. Implications for hemp breeding are discussed.

Introduction

From 16th to 18th century, hemp (*Cannabis sativa* L.) and flax (*Linum usitatissimum* L.) were the major fibre crops in Russia, Europe and North America (Pounds, 1979; Abel, 1980). Both crops were used for the production of fabrics for garments. Worn-out flax and hemp fabrics were used as raw materials in paper mills. However, the large-scale cultivation of cotton (*Gossypium* L.), jute (*Corchorus olitorius* L.) and other tropical fibres, caused the world area of hemp and flax to decline in the 19th century. This decline has continued in the 20th century, due to the advent of synthetic fibres. The presence of psychoactive components in hemp contributed to its decline, as this became a reason to prohibit hemp cultivation in many countries (Dempsey, 1975). In 1984, world hemp area was 403,000 ha, in 1993 it was 117,000 ha and in 2003 it had further declined to 74,000 ha (FAO, 2004). In spite of this overall decline, in Europe hemp area increased from 7,000 ha in 1993 to 18,000 ha in 2003 (Karus, 2004).

From the Second World War until the 1980's, hemp was a largely forgotten crop. However, in eastern and central Europe and in France breeding work continued (De Meijer, 1995), leading to more productive hybrid varieties, increased fibre contents (Bócsa, 1995) and very low contents of psychoactive substances (Fournier et al., 1987).

The potential of hemp as an attractive crop for sustainable fibre production was pointed out in the early 1980s (Hanson, 1980). Its yield was reported to be high, and it was said to improve soil structure (Du Bois, 1982). Furthermore, hemp was claimed to suppress weeds effectively, and to be virtually free from diseases or pests.

In January 1990, a comprehensive 4-year study was started in the Netherlands to investigate the potential of fibre hemp as a new raw material for the pulp and paper industry. This programme concluded that hemp is agronomically attractive, as most of the claims made by early hemp advocates proved to be true (van der Werf et al., 1995): hemp can supply high fibre yields, requires little or no pesticide and suppresses weeds and some major soil-borne diseases. However, in the maritime climate of the Netherlands the crop is not disease-free, as the fungus *Botrytis cinerea* can cause severe damage in wet years (van der Werf et al., 1995). In spite of this, hemp manifestly will fit into sustainable farming systems (van der Werf et al., 1996).

Intensive cotton production has been severely criticised for its negative effects on the environment: intensive use of pesticides (cotton can be treated 20 times per season), high fertiliser and irrigation requirements (Pimentel et al., 1991; WWF, 1999). These problems can be reduced to some extent by introducing integrated pest management techniques, or by shifting to organic farming methods (Pimentel et al., 1991; Pleydell-Bouverie, 1994). A comeback of hemp as a raw material for textile may contribute to the sustainability of the textile industry. Relative to cotton, hemp can be produced more sustainably, as it requires little or no pesticide and its fertiliser requirements are modest.

In November 2002, a comprehensive EU-funded 3-year study called Hemp-Sys was started (Amaducci, 2003). This project has the aim of promoting the development of a competitive, innovative and sustainable hemp fibre textile industry in the EU, by developing an improved, ecologically sustainable production chain, for high quality hemp fibre textiles, coupled to an integrated quality system for stems, raw and processed fibres, yarns and fabrics based on eco-labelling criteria. Given this objective, the project should include an assessment of the environmental impacts associated with the life cycle of hemp textile products.

Many studies have been conducted concerning the environmental impacts associated with the production of field crops such as wheat (*Triticum aestivum*) (Audsley et al., 1997), sugar beet (*Beta vulgaris*) (Brentrup et al., 2001) tomato (*Lycopersicon esculentum*) (Andersson et al., 1998) and biomass crops (Reinhardt & Zemanek, 2000). In fibre hemp, a single study was found (Patyk & Reinhardt, 1998): a screening Life Cycle Analysis of hemp products, including the processes: cultivation and harvest, pressing of oil, decortication, steam pressure digestion and textile production. Relative to the impacts associated with the whole of these processes, this preliminary study showed that crop production (i.e. cultivation and harvest) accounted for 17% of climate change, 36% of acidification and 10% of energy use. Unfortunately the study did not assess eutrophication associated with hemp products.

The present study aimed to quantify major impacts associated with the field production of fibre hemp using Life Cycle Analysis, and to compare the impacts of hemp to those of other annual crops. The effect of modifications of farmer practices and of a more favourable hypothesis with respect to nitrate leaching was explored. The results of this study will be of use for the evaluation of the environmental impacts of hemp products, and may help to guide future breeding programmes.

Materials and methods

Evaluation methodology

Environmental impacts associated with crop production were evaluated using Life Cycle Assessment (LCA), which is a method to assess impacts associated with a product by quantifying and evaluating the resources consumed and the emissions to the environment at all stages of its life cycle – from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product, to its reuse, recycling or final disposal (Guinée et al., 2002). In the Inventory Analysis phase, inputs from the environment (resources used) and outputs to the environment (emissions) associated with the product are listed. In the Impact Assessment phase, inputs and outputs are interpreted in terms of environmental impacts (Guinée et al., 2002).

The present study deals with the field production of fibre hemp and seven other major arable crops in France; only the processes up to (and including) the harvest, the transport to the farm and the on-farm drying of the harvested product (the latter applying only for maize) were considered. Emissions and resource use were expressed per ha.

Data concerning resource use and emissions associated with the production and delivery of several inputs for crop production (fertilisers, pesticides, tractor fuel, and agricultural machinery) were derived according to Nemecek and Heil (2001). The production of seed for sowing was taken into account, we assumed that inputs required for the production of seed for sowing were

Table 1. Inputs, yield and nitrate-N emitted (all in kg/ha) according to a Good agricultural practice production scenario for hemp and other major arable crops produced in France

	Hemp	Sunflower	Rape seed	Pea	Wheat	Maize	Potato	Sugar beet
N (ammonium nitrate)	75	85	110	0	130	100	170	220
P_2O_5 (triple superphosphate)	38	32	41	46	64	51	80	101
K_2O (potassium chloride)	113	21	30	95	90	30	293	180
CaO	333	167	167	333	333	333	0	333
Seed for sowing	55	5	2.5	200	120	20	2,000	2.5
Pesticide (active ingredient)	0	1.0	2.9	3.2	2.9	3.5	5.5	3.7
Diesel	65	79	81	87	101	91	165	137
Natural gas (for grain drying)	0	0	0	0	0	167	0	0
Agricultural machinery	16.4	23.0	23.3	26.9	28.7	21.3	29.0	34.2
Grain dry matter yield	–	2,100	2,970	4,110	5,910	6,440	–	–
Stem/straw dry matter yield	6,720	–	–	1,410	3,870	–	–	–
Sugar/tuber dry matter yield	–	–	–	–	–	–	10,000	11,540
Followed by catch crop (%) [1]	0	0	0	0	50	0	0	0
Succeeding crop	wheat	wheat	wheat	wheat	maize	wheat	wheat	wheat
NO_3-N emitted	40	40	40	70	40	40	40	40

[1] Indicates the percentage of cases for which a catch crop is assumed to be sown between harvest of the crop and sowing of the succeeding crop.

identical to those required for the production of the crop for which the seed was used as an input. When pig slurry was used as a fertiliser, emissions and resource use associated with its production and delivery were not included in this analysis, because they were allocated to pig production, as recommended by Wegener Sleeswijk et al. (1996). Data for energy carriers and for road transport were from the BUWAL 250 database (BUWAL, 1996). Buildings were not included in the analysis due to lack of data, the contribution of buildings to overall impacts of arable crops production has been shown to be minor (0–2%) (van Zeijts & Reus, 1996).

Crop production

For all crops, farmer practices were according to a reference scenario: Good Agricultural Practice, i.e. fertilisation according to anticipated crop needs, and integrated pest management. Input use for hemp was based on van der Werf (2002), for rape seed (*Brassica napus* L.), pea (*Pisum sativum* L.), wheat and maize (*Zea mays* L.) input use was based on interviews with experts (B. Goutte and A. Cottet, personal communication). Input use for sugar beet was based on Le Clech (1999), input use for sunflower (*Helianthus annuus*) was according to Cederberg (1998), input use for potato (*Solanum tuberosum* L.) was according to ITCF (1995). Yield levels were averages for 1996–2000 (AGRESTE, 2001; FAO, 2002). Input use and yield levels for the crops are summarised in Table 1.

For hemp, the effect of modifications of farmer practices (use of pig slurry and reduced tillage) and of reduced nitrate leaching was explored. The environmental impacts of the reference scenario (Good Agricultural Practice) were compared to three alternative scenarios (Table 2).

Emissions associated with crop production

Ammonia emissions due to application of ammonium nitrate fertiliser were estimated according to ECETOC (1994): emission factor (EF) was 0.02 kg of NH_3-N per kg N applied. Total ammonia nitrogen (TAN $= NH_3 + NH_4^+$) content of applied pig slurry was 3.17 kg/t. EF for NH_3 volatilisation following field application of slurry (on cultivated soil in early April, incorporation within 24 h) was 0.15 kg of NH_3-N per kg of TAN (Morvan & Leterme, 2001).

With respect to losses of nitrate nitrogen (NO_3-N) to groundwater (Table 1), crops were assigned to one of four leaching risk classes: very minor (15 kg/ha), minor (40 kg/ha), moderate (70 kg/ha) and large (100 kg/ha). Assignment of leaching risk was based on crop-specific values of NO_3 present in the soil at harvest

Table 2. Inputs, yield and nitrate-N emitted (all in kg/ha) according to four production scenarios for hemp produced in France

	Good agricultural practice	Pig slurry	Reduced tillage	Less leaching
Pig slurry		20,000		
N (ammonium nitrate)	75	0	75	75
P_2O_5 (triple superphosphate)	38	0	38	38
K_2O (potassium chloride)	113	51	113	113
CaO	333	333	333	333
Seed for sowing	55	55	55	55
Pesticide (active ingredient)	0	0	0	0
Diesel	65	72	39	65
Agricultural machinery	16.4	18.8	11.6	16.4
Straw dry matter yield	6,720	6,720	6,720	6,720
Followed by catch crop (%)[1]	0	0	0	0
Succeeding crop	wheat	wheat	wheat	wheat
NO_3-N emitted	40	40	40	20

All scenarios assume *Good Agricultural Practice*.
[1]Indicates the percentage of cases for which a catch crop is assumed to be sown between harvest of the crop and sowing of the succeeding crop.

in autumn, leaching losses calculated with the LIXIM simulation model (Mary et al., 1999), and the length of the period between harvest and the establishment of the succeeding (catch) crop.

Emissions of nitrous oxide nitrogen (N_2O-N) were estimated according to Mosier et al. (1998): for direct emissions from soils EF was 0.0125 kg of N_2O-N per kg N input from synthetic and organic fertiliser and biological N-fixation, after subtraction of ammonia emissions EF was 0.01 kg of N_2O-N per kg of NH_3-N emitted and 0.025 kg of N_2O-N per kg of NO_3-N emitted. Emissions of nitric oxide nitrogen (NO_x-N) were estimated according to Rossier (1998) at 10% of emissions of N_2O-N.

Run-off of PO_4-P to surface water was estimated according to Rossier (1998): an EF of 0.01 kg of PO_4-P per kg P input from synthetic and organic fertiliser was used. Emissions of Cd, Cu, Ni, Pb and Zn to the soil were calculated according to a balance approach, considering input by synthetic and organic fertilisers and output via harvested produce. Heavy metal content of fertilisers was based on Rossier (1998), except for Cu and Zn in slurry, which were based on Baudet (1999). Data on heavy metal uptake of crops were rare. Therefore the same reference uptake was used regardless of the crop. Reference uptake was based on a wheat crop yielding 6800 kg/ha of grain containing 0.12 mg/kg of Cd, 5.9 mg/kg of Cu, 0.22 mg/kg of Ni, 0.2 mg/kg of Pb and 31 mg/kg of Zn (contents based on Audsley et al., 1997 and Baize, personal communication). Pesticides and their metabolites were not taken into account in this study, as appropriate characterisation factors are lacking for many substances.

Characterisation factors

In the Life Cycle Impact Assessment phase, it is first determined which impact categories will be considered. In this study the following impact categories were considered: eutrophication, climate change, acidification, terrestrial ecotoxicity, energy use and land use. Next, the indicator result for each impact category is determined. This is done by multiplying the aggregated resources used and the aggregated emissions of each individual substance with a characterisation factor for each impact category to which it may potentially contribute (Heijungs et al., 1992). Characterisation factors are substance-specific, quantitative representations of the additional environmental pressure per unit emission of a substance (Huijbregts et al, 2000). The characterisation factors used in this study are given below for each impact category.

Eutrophication covers all potential impacts of high environmental levels of macronutrients, in particular N and P. As recommended by Guinée et al. (2002), Eutrophication Potential (EP) was calculated using the generic EP factors in kg PO_4-equivalents., NH_3: 0.35, NO_3: 0.1, NO_2: 0.13, NO_x: 0.13, PO_4: 1.

Climate change was defined here as the impact of emissions on the heat radiation absorption of the atmosphere. As recommended by Guinée et al. (2002), Global Warming Potential for a 100 year time horizon (GWP_{100}) was calculated according to the GWP_{100} factors by IPCC (Houghton et al., 1996) in kg CO_2-equivalents, CO_2: 1, N_2O: 310, CH_4: 21.

Acidifying pollutants have a wide variety of impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials (buildings). As recommended by Guinée et al. (2002), Acidification Potential (AP) was calculated using the average European AP factors by Huijbregts (1999a) in kg SO_2-equivalents, NH_3: 1.6, NO_2: 0.5, NO_x: 0.5, SO_2: 1.2.

Terrestrial ecotoxicity refers to impacts of toxic substances on terrestrial ecosystems. As recommended by Guinée et al. (2002), Terrestrial EcoToxicity Potential (TETP) was calculated using the TETP factors for infinite time horizon and global scale by Huijbregts (1999b) in kg 1,4-dichlorobenzene-equivalents (DCB-eq.), Cd: 170, Cu: 14, Ni: 240, Pb: 33, Zn: 25.

Energy use refers to the depletion of energetic resources. Energy use was calculated using the Lower Heating Values proposed in the SimaPro 1.1 method (PRé Consultants, 1997), crude oil: 42,6 MJ/kg, natural gas: 35 MJ/m^3, uranium: 451000 MJ/kg, coal: 18 MJ/kg, lignite: 8 MJ/kg, gas from oil production 40.9 MJ/m^3.

Land use refers to the loss of land as a resource, in the sense of being temporarily unavailable for other purposes due to the growing of crops. This is a quantitative assessment, which does not distinguish quality of land use.

Results

Input use and impacts for eight annual crops

Input use was quite variable for the crops (Table 1): from 0 (pea) to 220 (sugar beet) kg/ha for N, from 32 (sunflower) to 101 (sugar beet) kg/ha for P_2O_5, from 0 (hemp) to 5.5 (potato) kg/ha for pesticide active ingredient, and from 65 (hemp) to 165 (potato) kg/ha for diesel. Hemp and sunflower can be consistently characterised as low-input crops, whereas potato and sugar beet can be characterised as high-input crops.

Impacts were very variable, depending on the crop (Table 3). Differences were smallest for land use (range 10,000–10,500) and largest for terrestrial ecotoxicity (range 0.1–6.7). For climate change (range 2,300–4,900), acidification (range 8.3–24.5) and energy use (range 11,400–26,300) variability was quite large, for eutrophication (range 20.2–34.4) it was relatively modest.

Eutrophication was low (about 20 kg PO_4-eq.) for hemp, sunflower and rape seed, and high (34 kg PO_4-eq.) for pea (Table 3). Climate change was low for hemp and sunflower (2300 kg CO_2-eq.) and high for potato (4120) and sugar beet (4900). Acidification was low for pea, hemp and sunflower (8–11 kg SO_2-eq.) and high for potato and sugar beet (22–25). Terrestrial ecotoxicity was very low for pea (0.1 kg 1,4-DCB-eq.), low for sunflower, hemp and rape seed (1.8–2.5) and high for potato and sugar beet (4.9–6.7). Energy use was low for hemp, pea and sunflower (11,400–11,900 MJ), and high for maize, potato and sugar beet (23,000–26,300). For land use differences were negligible.

For all impact categories (except land use), values were consistently low for hemp and sunflower, and consistently high for potato and sugar beet. For rape seed and pea, the impact values were rather low, and for wheat and maize impacts were of intermediate level.

Table 3. The environmental impacts due to the field production of hemp (1 ha) and other major arable crops in France, according to a Good agricultural practice production scenario

Impact category	Unit	Hemp	Sunflower	Rape seed	Pea	Wheat	Maize	Potato	Sugar beet
Eutrophication	kg PO_4-eq.	20.5	20.2	20.6	34.4	21.9	21.0	23.8	24.1
Climate change	kg CO_2-eq.	2,330	2,300	2,700	2,890	3,370	3,280	4,120	4,900
Acidification	kg SO_2-eq.	9.8	10.8	12.8	8.3	16.3	13.6	22.4	24.5
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	2.3	1.8	2.5	0.1	4.0	3.0	4.9	6.7
Energy use	MJ	11,400	11,900	13,800	11,800	18,100	23,000	25,600	26,300
Land use	m^2.year	10,200	10,000	10,000	10,500	10,200	10,100	10,400	10,200

Table 4. The contribution of the field production of 1 ha of hemp to environmental impacts in western Europe for six impact categories

Impact category	Unit	Annual per capita impacts	Reference for annual per capita impacts	Contribution (%)
Eutrophication	kg PO_4-eq.	38.4	Huijbregts et al., 2001	53.3
Climate change	kg CO_2-eq.	14,600	Huijbregts et al., 2001	15.9
Acidification	kg SO_2-eq.	84.2	Huijbregts et al., 2001	11.7
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	146	Huijbregts et al., 2001	1.6
Energy use	MJ	154,000	PRé Consultants, 1997	7.4
Land use	m^2.year	10,100	Huijbregts et al., 2001	101.4

Contributions are calculated by dividing impacts for 1 ha of hemp (Table 2) by annual per capita impacts for western Europe in 1995.

Relative contribution of hemp field production to overall impacts in western Europe

In order to assess the relative contribution of hemp crop production to overall environmental impacts in Europe, impacts for the field production of 1 ha of hemp were divided by the total impacts per person for western Europe in 1995 (Huijbregts et al., 2001; PRé Consultants, 1997) (Table 4). This normalisation revealed that the contribution of hemp production to land use (101%) and eutrophication (53%) was very important, and that its contribution to terrestrial ecotoxicity was minor (1.6%). Its contribution to energy use (7%), acidification (12%) and climate change (16%) was intermediate.

The contribution of emitted substances to impacts

The contribution of emitted substances and resources used to impact values was examined for hemp (characterised by low impact values), wheat (intermediate impact values) and sugar beet (high impact values) (Table 5). For the three crops, eutrophication was mainly (75–89%) due to NO_3. Climate change was

Table 5. The contributions (in %) to different impact categories of emitted substances and resource use associated with the field production of hemp, wheat and sugar beet

Impact category	Substances/ resources	Hemp	Wheat	Sugar beet
Eutrophication	NO_3	88.6	82.4	75.1
	NH_3	3.1	5.1	7.9
	PO_4	3.4	5.4	7.7
	NO_2	4.9	7.1	9.3
Climate change	N_2O	56.2	56.6	58.7
	CO_2	42.8	42.3	40.3
	CH_4	1.0	1.1	1.0
Acidification	NH_3	29.9	31.6	35.5
	SO_2	31.1	31.9	29.7
	NO_2	39.0	36.5	34.8
Terrestrial ecotoxicity	Zn	0	0	2.4
	Ni	70.2	67.5	65.7
	Pb	3.5	4.0	3.2
	Cd	26.3	28.5	28.7
Energy use	Crude oil	44.7	45.8	43.7
	Natural gas	32.7	32.1	36.4
	Uranium	11.4	10.6	9.0
	Coal	9.3	9.5	8.8
	Others	1.9	2.0	2.1

mainly due to N_2O (56–59%) and CO_2 (40–43%). Acidification was due to emissions of NH_3, SO_2, and NO_2, with the three substances contributing similarly. Terrestrial ecotoxicity was mainly due to emissions of Ni (66–70%) and Cd (26–29%). Energy use was mainly due to crude oil (44–46%) and natural gas (32–36%).

Although the three crops differed strongly with respect to the use of inputs and the level of impact values obtained, only minor differences were found for the relative contribution of substances and resources to impacts.

The contribution of processes to impacts

The contribution of processes (production of crop inputs, production and use of diesel, and field emissions) was examined for hemp (low impacts), wheat (intermediate impacts) and sugar beet (high impacts) (Table 6). For the three crops eutrophication was very largely (90–95%) due to field emissions. Climate change was mainly due to field emissions (38–41%), N fertiliser production (25–34%), diesel production and use (11%) and CaO production (6–13%). Acidification

Table 6. The contributions (in %) to different impact categories of the processes (production of crop inputs, production and use of diesel, field emissions) making up the field production of hemp, wheat and sugar beet

Impact category (unit)	Processes	Hemp	Wheat	Sugar beet
Eutrophication	N fertiliser production	1.0	1.5	2.4
	P fertiliser production	1.1	1.7	2.5
	K fertiliser production	0.1	0.1	0.1
	CaO production	0.2	0.2	0.2
	Pesticide production	0	0.1	0
	Machinery production	0.2	0.4	0.4
	Diesel production and use	2.7	4.0	4.9
	Field emissions[1]	94.7	92.0	89.5
Climate change	N fertiliser production	24.6	29.5	34.4
	P fertiliser production	2.8	3.3	3.5
	K fertiliser production	2.6	1.4	1.9
	CaO production	13.1	9.0	6.2
	Pesticide production	0	0.6	0.5
	Machinery production	5.3	6.4	5.3
	Diesel production and use	10.5	11.3	10.5
	Field emissions[1]	41.1	38.5	37.7
Acidification (kg SO_2-eq.)	N fertiliser production	11.8	12.4	14.0
	P fertiliser production	10.7	10.8	11.3
	K fertiliser production	2.2	1.1	1.4
	CaO production	3.3	2.0	1.3
	Pesticide production	0	1.7	1.4
	Machinery production	12.5	13.3	10.5
	Diesel production and use	26.2	24.4	22.1
	Field emissions[1]	33.3	34.3	38.0
Energy use (MJ)	N fertiliser production	28.1	30.7	35.9
	P fertiliser production	5.6	6.0	6.5
	K fertiliser production	9.8	4.9	6.8
	CaO production	8.5	5.3	3.6
	Pesticide production	0	4.2	3.7
	Machinery production	19.3	21.2	17.5
	Diesel production and use	28.7	27.7	26.0

[1]All field emissions, except for those resulting from the field use of diesel, which are accounted for in "Diesel production and use."

was mainly due to field emissions (33–38%), diesel production and use (22–26%), N fertiliser production (12–14%), P fertiliser production (11%) and machinery production (11–13%). Terrestrial toxicity was due exclusively to field emissions (data not shown). Energy use was mainly due to N-fertiliser production (28–36%), diesel production and use (26–29%) and machinery production (18–21%).

Although the three crops differed strongly with respect to the use of inputs and the level of impact values obtained, only minor differences were found for the relative contribution of processes to impacts.

The effect of alternative scenarios for hemp production

In many areas pig slurry is available at very low cost, its use may reduce production costs. Substitution of mineral fertiliser by pig slurry strongly reduced climate change (−24%) and energy use (−32%) but increased eutrophication (+16%), acidification (+140%) and terrestrial ecotoxicity (+1720%) (Table 7). Reduced tillage is of interest to farmers as it reduces erosion, production costs and labour requirements. The reduced tillage scenario affected *climate change* (−6%), acidification (−13%) and energy use (−16%).

The amount of nitrate leached, associated with an arable crop, will be lower when the amount of nitrate left in the soil at harvest is small, when the length of the period between harvest and the next crop is short or when the precipitation during this period is reduced. The scenario assuming reduced leaching reduced eutrophication (−43%) and climate change (−10%).

Discussion

This study compared the potential environmental impacts of fibre hemp to the impacts of seven major arable crops, in the context of farmer practices and pedoclimatic conditions of France. Quantitative information on the environmental impact of hemp field production is scarce. Patyk and Reinhardt (1998) carried out a preliminary LCA of hemp production for Germany, supplying results for energy use, climate change and acidification. Their result for energy use (12,300 MJ/ha) is close to our result (11,400), the values they obtained for acidification (6.6 kg SO_2-eq.) and for climate change (1421 kg CO_2-eq.) are lower than the results reported here (9.8 and 2330, respectively). Patyk and Reinhardt (1998) do not give sufficient methodological detail to allow an analysis of the reasons for this discrepancy.

This study has revealed major differences in input use and environmental impacts for the crops compared. Further, it has been shown that low-input crops tend to be also low impact crops, whereas high-input crops have high impacts. Hemp and sunflower are low-input crops, with respect to the use of fertilisers, pesticides, diesel and agricultural machinery. These two crops have consistently lower impact values than the other crops studied, for all impact categories examined here, with the exception of land use. Land use is the only impact category for which all the crops studied show only minor differences. This is not surprising, as the only origin for the differences found in land use lies in the land surface required for the production of seed for sowing one hectare of the crop. Although this surface is quite different from one crop to another (it may vary from 10 to 500 m^2), its overall contribution to land use is small, relative to the 10,000 m^2 required to grow the crop.

A detailed comparison of hemp (a low-impact crop), wheat (of intermediate impact) and sugar beet (high-impact) revealed that, despite major differences in the level of impact values, only minor differences were found both for the relative contribution of substances and resources to impacts, as well as for the relative contribution of processes to impacts.

Table 7. The environmental impacts due to the field production (1 ha) of hemp according to four production scenarios

Impact category	Unit	Good agricultural practice	Pig slurry	Reduced tillage	Less leaching
Eutrophication	kg PO_4-eq.	20.5	23.7	20.2	11.6
Climate change	kg CO_2-eq.	2,330	1,770	2,200	2,090
Acidification	kg SO_2-eq.	9.8	23.5	8.5	9.8
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	2.3	41.9	2.3	2.3
Energy use	MJ	11,400	7,760	9,520	11,400
Land use	m^2.year	10,200	10,200	10,200	10,200

Although the environmental impacts associated with the production of fibre hemp are smaller than those associated with most other crops, an examination of possible pathways to further reduce hemp's impacts is of obvious interest. Relative to the overall environmental impacts in Europe, the contribution of hemp production to land use (101%) and eutrophication (53%) is very important. However, the importance of the land use impact category will depend on the regional and national context. In a densely populated country, like for instance the Netherlands, agriculture, industry, housing and infrastructure compete for land, and land use is considered to be at least as important as the other impact categories. In France, on the other hand, competition for land is less, and land use is of secondary importance. Eutrophication, however, is considered a major problem in France, as elsewhere in Europe. While hemp's contribution to terrestrial ecotoxicity was minor (1.6%), its contribution to energy use (7%), acidification (12%) and climate change (16%) was found to be intermediate. A reduction of the environmental impacts associated with the production of hemp should therefore give priority to reduction of eutrophication, and consider the reduction of climate change, acidification and energy use as secondary objectives.

Given this objective, the substitution of mineral fertiliser by pig slurry is not an appropriate option, as, although it decreases climate change and energy use (both due to a reduced use of mineral fertiliser), this comes at the prize of an increase in eutrophication and a major increase in acidification, both of which are caused by the fact that the use of slurry leads to much larger emissions of NH_3 than the use of mineral fertiliser. Finally, the use of slurry brings about a major increase in terrestrial ecotoxicity, due to the presence of Cu and Zn in pig slurry. Although the use of slurry instead of mineral fertiliser may be of economic interest, its overall effect on the environmental performance of hemp is negative.

The introduction of reduced tillage is an appropriate option. Although it does not affect eutrophication, it does reduce energy use, acidification and climate change. These effects result from the reduced use of diesel and agricultural machinery. Reduced tillage furthermore generates additional environmental benefits, such as reduced erosion risks and increased soil organic matter content (Uri et al., 1998).

Any measures leading to a reduction in NO_3 leaching are of high interest, as a 50% reduction of the amount of NO_3 leached reduced eutrophication by 43% and climate change by 10%. Whereas the reduction of eutrophication results directly from a lower emission of NO_3, the effect on climate change is indirect, resulting from reduced emission of N_2O due to denitrification of NO_3. In general, the optimisation of nitrogen fertilisation and the reduction of the period between harvest and the establishment of the next (catch) crop are the principal measures recommended to reduce NO_3 leaching (Gustafson et al., 2000). However, fertilisation was optimised in our scenarios, therefore a rapid establishment of the next crop or of a catch crop seems the most promising measure to reduce nitrate emissions.

Future breeding efforts may also contribute to reducing the environmental impacts of hemp production, in particular by carrying out breeding programmes under conditions of reduced inputs. Our results have shown that it would be of particular interest to focus on conditions combining lower nitrogen fertilisation levels (limiting nitrate leaching) and reduced soil tillage. Genotypic variability has been demonstrated for both nitrogen uptake and nitrogen use efficiency in wheat (Le Gouis et al., 2000), maize (Singh et al., 1998) and many other crops. An exploration of variability for this trait in hemp would be of major interest. Although we did not find any results assessing genotypic variability relative to crop performance under conditions of reduced tillage, we think this might also be a promising path to explore, for the creation of future hemp cultivars.

Conclusions

This study assumed crop production practices according to Good Agricultural Practise (GAP). GAP in France is largely similar to GAP elsewhere in western Europe; therefore we conclude that the results of this study, though based on data from France, can be considered to hold true more generally for all of western Europe.

Relative to the other crops examined in this study, hemp and flax are low-input and low-impact crops. The difference is most important relative to potato and sugar beet, which can be characterised as high-input and high-impact crops.

In spite of major differences among the crops with respect to the level of impact values, only minor differences were found both for the relative contribution of substances and resources to impacts, as well as for the relative contribution of processes to impacts.

A reduction of the environmental impacts associated with the production of hemp should give priority to reduction of eutrophication, and consider the reduction of climate change, acidification and energy use as secondary objectives.

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References

Abel, E.L., 1980. Marihuana, the First Twelve Thousand Years. Plenum Press, NY, U.S.A.

AGRESTE, 2001. Tableaux de l'Agriculture Bretonne 2001. Direction Régionale de l'Agriculture et de la Forêt, Service Régional de Statistique Agricole, Rennes, France.

Amaducci, S., 2003. HEMP-SYS: Design, development and up-scaling of a sustainable production system for hemp textiles – An integrated quality systems approach. J Ind Hemp 8 (2): 79–83.

Andersson, K., T. Ohlsson & P. Olsson, 1998. Screening life cycle assessment (LCA) of tomato ketchup: A case study. J Clean Prod 6(3–4): 277–288.

Audsley, E., S. Alber, R. Clift, S. Cowell, P. Crettaz, G. Gaillard, J. Hausheer, O. Jolliett, R. Kleijn, B. Mortensen, D. Pearce, E. Roger, H. Teulon, B. Weidema & H. van Zeijts, 1997. Harmonisation of environmental life cycle assessment for agriculture. Final Report Concerted Action AIR3-CT94-2028. Silsoe Research Institute, Silsoe, U.K.

Baudet, J.J., 1999. Effluents d'élevage, des compositions très variables. Oléoscope 54: 10–11.

Bócsa, I., 1995. Die Hanfzüchtung in Ungarn: Zielersetzungen, Methoden und Ergebnisse. In: M. Karus (Ed.) Bioresource Hemp Symposium Reader, 2nd Edn., Nova-Institut, Frankfurt, Germany, pp. 200–215.

Brentrup, F., J. Küsters, H. Kuhlmann & J. Lammel, 2001. Application of the Life Cycle Methodology to agricultural production: An example of sugar beet production with different forms of nitrogen fertilisers. Eur J Agronom 14: 221–233.

BUWAL, 1996. Ökoinventare für Verpackungen. Schriftenreihe Umwelt Nr. 250/1+2, Bundesamt für Umwelt, Wald und Landschaft, Bern, Switzerland.

Cederberg, C., 1998. Life cycle assessment of milk production. A comparison of conventional and organic farming. SIK Report 643, Götenburg, Sweden.

De Meijer, E.P.M., 1995. Fibre hemp cultivars: A survey of origin, ancestry, availability and brief agronomic characteristics. J Int Hemp Assoc 2: 66–73.

Dempsey, J. M., 1975. Hemp. In: Fiber Crops, University of Florida Press, Gainesville, Florida, U.S.A., pp. 46–89.

Du Bois, W.F., 1982. Hennep als grondstof voor de papierindustrie. [Hemp as a raw material for the paper industry.] Bedrijfsontwikkeling 13: 851–856.

ECETOC, 1994. Ammonia emissions to air in western Europe. Technical Report N. 62. European Chemical Industry Ecology & Toxicology Centre, Brussels, Belgium.

FAO, 2004. FAOSTAT Agriculture Data. Available at: http://faostat.fao.org/.

FAO, 2002. Technical Conversion Factors (TCF) for agricultural commodities. Available at : http://www.fao.org/WAICENT/FAOINFO/ECONOMIC/ESS /tcf.pdf.

Fournier, G., C. Richez-Dumanois, J. Duvezin, J.P. Mathieu & M. Paris, 1987. Identification of a new chemotype in *Cannabis sativa*: Cannabigerol-dominant plants, biogenetic and agronomic prospects. Planta Medica 53: 277–280.

Guinée, J.B., M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, H. de Bruijn, R. van Duin & M.A.J. Huijbregts, 2002. Handbook on Life Cycle Assessment. An Operational Guide to the ISO Standards. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Gustafson, A., S. Fleischer & A. Joelsson, 2000. A catchment-oriented and cost-effective policy for water protection. Ecol Eng 14: 419–427.

Hanson, J., 1980. An outline for a U.K. hemp strategy. The Ecologist 10: 260–263.

Heijungs, R., J.B. Guinée, G. Huppes, R.M. Lankreijer, H.A. Udo de Haes, A. Wegener Sleeswijk, A.M.M. Ansems, P.G. Eggels, R. van Duin & H.P. Goede, 1992. Environmental Life Cycle Assessment of Products, I Guide, II Backgrounds. Centre of Environmental Science, Leiden, The Netherlands.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg & K. Maskell, 1996. Climate Change 1995: The Science of Climate Change. Cambridge University Press, Cambridge, U.K.

Huijbregts, M.A.J., 1999a. Life-cycle impact assessment of acidifying and eutrophying air pollutants. Calculation of characterisation factors with RAINS-LCA. Interfaculty Department of Environmental Science, Faculty of Environmental Science, University of Amsterdam, Amsterdam, The Netherlands.

Huijbregts, M.A.J., 1999b. Priority assessment of toxic substances in LCA. Development and application of the multi-media fate, exposure and effect model USES-LCA. IVAM Environmental Research, University of Amsterdam, Amsterdam, The Netherlands.

Huijbregts, M.A.J., W. Schöpp, E. Verkuijlen, R. Heijungs & L. Reijnders, 2000. Spatially explicit characterisation of acidifying and eutrophying air pollution in life-cycle assessment. J Ind Ecology 4(3): 125–142.

Huijbregts, M.A.J., G. Huppes, A. de Koning, L. van Oers & S. Suh, 2001. LCA Normalisation Factors for the Netherlands, Europe and the World. Centre of Environmental Science, Leiden University, Leiden, Netherlands.

ITCF, 1995. La culture de la pomme de terre de conservation. Institut Technique des Céréales et des Fourrages, Institut Technique de la Pomme de Terre, Paris, France.

Karus, M., 2004. First International Conference of the European Industrial Hemp Association (EIHA). J Ind Hemp, 9(1), 117–121.

Le Clech, B., 1999. Productions végétales. Grandes cultures. Editions Synthèse Agricole, Bordeaux, France.

Le Gouis, J., D. Béghin, E. Heumez & P. Pluchard, 2000. Genetic differences for nitrogen uptake and nitrogen utilisation efficiencies in winter wheat. Europ J Agronomy 12:163–173.

Mary, B., N. Beaudoin, E. Justes & J.M. Machet, 1999. Calculation of nitrogen mineralization and leaching in fallow soil using a simple dynamic model. Europ J Soil Sci 50: 549–566.

Morvan, T. & P. Leterme, 2001. Vers une prévision opérationnelle des flux d'azote résultant de l'épandage de lisier : Paramétrage d'un modèle dynamique de simulation des transformations de l'azote des lisiers. Ingéniéries 26: 17–26.

Mosier, A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger & O. van Cleemput, 1998. Closing the global N_2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle. Nutr Cycl Agroecosyst 52: 225–248.

Nemecek, T. & A. Heil, 2001. SALCA – Swiss Agricultural Life Cycle Assessment Database. Version 012, December 2001. FAL, Swiss Federal Research Station for Agroecology and Agriculture, Zuerich, Switzerland.

Patyk, A. & G.A. Reinhardt, 1998. Life cycle assessment of hemp products. In D. Ceuterick (Ed.) International conference on life cycle assessment in agriculture, agro-industry and forestry. Proceedings. Brussels, Belgium pp. 39–44.

Pimentel, D., L. McLaughlin, A. Zepp, B. Lakitan, T. Kraus, P. Kleinman, F. Vancini, W.J. Roach, E. Graap, W.S. Keeton & G. Selig, 1991. Environmental and economic impacts of reducing U.S. agricultural pesticide use. In: D. Pimentel (Ed.) CRC Handbook of Pest Management in Agriculture, 2nd edn., pp. 679–718. CRC Press, Boca Raton, Florida, U.S.A.

Pleydell-Bouverie, J. 1994. Cotton without chemicals. New Scientist, 24 September 1994: 25–29.

Pounds, N.J.G., 1979. An Historical Geography of Europe 1500–1840. Cambridge University Press, Cambridge, U.K.

PRé Consultants, 1997. SimaPro 2 Method. Database Manual. Pré Consultants B.V., Amersfoort, The Netherlands.

Reinhardt, G., G. Zemanek, 2000. Ökobilanz Bioenergieträger. Basisdaten, Ergebnisse, Bewertungen. Erich Schmidt Verlag, Berlin, Germany.

Rossier, D., 1998. Ecobilan. Adaptation de la méthode écobilan pour la gestion environnementale de l'exploitation agricole. Service Romand de Vulgarisation Agricole, Lausanne, Switzerland.

Singh, U., J.K. Ladha, E.G. Castillo, G. Punzalan, A. Tirol-Padre & M. Duqueza, 1998. Genotypic variation in nitrogen use efficiency in medium- and long-duration rice. Field Crops Res 58: 35–53.

Uri, N.D., J.D. Atwood & J. Sanabria, 1998. The environmental benefits and costs of conservation tillage. Sci Total Env 216: 13–32.

van der Werf, H.M.G., W.C.A. van Geel & M. Wijlhuizen, 1995. Agronomic research on hemp (*Cannabis sativa* L.) in the Netherlands, 1987–1993. J Int Hemp Assoc 2: 14–17.

van der Werf, H.M.G., E.W.J.M. Mathijssen & A.J. Haverkort, 1996. The potential of hemp (*Cannabis sativa* L.) for sustainable fibre production: A crop physiological appraisal. Ann Appl Biol 129: 109–123.

van der Werf, H.M.G., 2002. Hemp production in France. J Ind Hemp 7 (2): 105–109.

van Zeijts, H. & J.A.W.A. Reus, 1996. Toepassing van LCA voor Agrarische Produkten. 4a. Ervaringen met de methodiek in de case akkerbouw. LEI-DLO, Den Haag, Netherlands.

Wegener Sleeswijk, A., R. Kleijn, M.J.G. Meeusen-van Onna, H. Leneman, H.H.W.J.M. Sengers, H. van Zeijts & J.A.W.A. Reus, 1996. Application of LCA to agricultural products; 1. Core methodological issues; 2. Supplement to the LCA guide; 3. Methodological background. Centre of Environmental Science, Leiden University, Leiden, Netherlands.

WWF, 1999. The impact of cotton on fresh water resources and ecosystems. A preliminary synthesis. Background paper. World Wildlife Fund, Gland, Switserland.