J1

My name is Bonnie Carroll. I have lived in Arcata for 24 years and am planning to stay here through retirement.

I am a psychotherapist with a private practice in McKinleyville.

I smoked pot when I was a teen but quit about 22. It had a weird effect on me and left me feeling uncomfortable. I didn't use it again until about 2 years ago when a friend had me to try it for my crippling insomnia and pain

So I took a small bite of cbd/thc chocolate, and within an hour I felt better than I had for years.

About 5 years ago, I was diagnosed with Hashimoto's: an autoimmune disorder of the thyroid.

But after treatment started, I still wasn't ok. More testing found that I had Rheumatoid arthritis. I went to UCSF where they tested every single organ, muscle, and joint I have. But they couldn't figure out what was wrong with me. Because, even though I was very sick, I didn't have the joint damage that accompanies RA.

The doctors were stumped. At this point I had been using cannabis for almost a year and a half.

I told my doctor how cannabis affects my body: one hit of the right strain of cannabis, is like an epidural and all my pain goes away. My UCSF rheumatologist exclaimed that I must have fibromyalgia because that is exactly how the right strain of cannabis effects fibromyalgia pain.

I researched fibromyalgia and that is what I have: widespread crippling pain, horrible insomnia, and an assortment of other disabling symptoms. Both my Primary care doctor and UCSF Rheumatologist agreed that a super healthy diet, cannabis and a few pharmaceuticals was to be my treatment plan. Everything was great at first. I had wonderful access to good medicinal, high CBD cannabis through HPRC. And while it was expensive, it was about the same as my other prescribed medications.

But on July 1st of 2018, something changed. I believe that the cost of the new testing requirements, taxation and fees effected the profit margins, so growers focused on the high thc recreational cannabis strains that sell better.

Since July 1st, I have not been able to find any low thc medicinal strains, and the cost of all the products that are available increased to the point where it is difficult for me to purchase any cannabis medicine.

I know people in the legal grow industry who can't find any CBD flowers. Apparently, growers stopped growing and/or testing their CBD flowers for retail. I have only been able to find a couple of high CBD, low THC strains, and they weren't even that good. Not as good as the medicinal strains used to be.

So I am here today to let you know that it would be very helpful if you reduced the fees and/or taxes on the medicinal cannabis strains that have lower THC levels.

My goal is to have pain relief with minimal cognitive distortion.

I do prefer to live life sober and so do many other medical cannabis users.

Thank You.

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Hemp: A more sustainable annual energy crop for climate and energy policy

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HIGHLIGHTS

- The GHG burden of hemp is intermediate between perennial and annual energy crops.
- Replacing 25% of OSR/beet with hemp could increase GHG abatement by 21 Mt/CO_2eq./year.
- Hemp is a more efficient bioenergy feedstock than the dominant annual energy crops.

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ABSTRACT

The objective of this study was to compare the fuel-chain greenhouse gas balance and farm economics of hemp grown for bioenergy with two perennial bioenergy crops, Miscanthus and willow, and two more traditional annual bioenergy crops, sugar beet and oil seed rape (OSR). The GHG burden of hemp cultivation is intermediate between perennial and traditional annual energy crops, but net fuel chain GHG abatement potential of 11 t/CO_2 eq./ha/year in the mid yield estimate is comparable to perennial crops, and 140% and 540% greater than for OSR and sugar beet fuel chains, respectively. Gross margins from hemp were considerably lower than for OSR and sugar beet, but exceeded those from Miscanthus when organic fertilizers were used and in the absence of establishment grants for the latter crop. Extrapolated up to the EU scale, replacing 25% of OSR and sugar beet production with hemp production could increase net GHG abatement by up to 21 Mt CO_2eq./year. Hemp is a considerably more efficient bioenergy feedstock than the dominant annual energy crops. Integrated into food crop rotations, hemp need not compete with food supplies, and could provide an appealing option to develop more sustainable non-transport bioenergy supply chains.

1. Introduction

Growing evidence of the effect of increasing greenhouse gas emissions on climate (Solomon et al., 2007) together with rising energy prices and increasing dependence on fossil fuels are driving countries to consider renewable forms of energy, including bioenergy. Given the shortage of biomass from forestry production, and limited suitable "waste" streams, energy crops are likely to play a major part in the future bioenergy mix (Clifton-Brown et al., 2007).

Two energy crops for heat and electricity production in Northern Europe which have achieved popularity are the perennial energy grass Miscanthus and willow. Both these energy crops have high establishment costs (2500 euro/ha) but are expected to remain viable for up to 20 years (Bullard and Metcalf, 2001; Dawson, 2007). Suitable energy crops should deliver a good final energy ratio, offering high useful energy yields and require a low energy input for cultivation and processing. Both Miscanthus and willow are examples of more sustainable energy crops, as high yields of biomass can be obtained using relatively low inputs. Their perennial nature avoids emissions associated with annual cultivation and permits reserves of soil carbon to be maintained, or to accumulate, within the soil.

Although, energy markets are still developing, farmers have been attracted to the idea of growing energy crops because of falling farm incomes together with the promise of a strong future market for bioenergy products. High initial investment costs together with a land commitment of 15–20 years, however, do not suit all farmers and may discourage some from considering energy crops. Consequently, there is an interest to explore alternative annual energy crops with low establishment costs that could fit in to standard crop rotations.

Break crops are used by tillage farmers to improve disease and weed control, as well as to improve soil structure. This practice is

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well known to increase the yield of subsequent crops such as wheat by as much as 20% (Kirkegaard et al., 2008). In Northern Europe, sugar beet and oilseed rape are popular break crops used in cereal rotations. However, European sugar beet acreage has reduced by approximately one third since 2006 when the EU reformed the European sugar beet industry E.U. (2006). The consequence of this reform was that some countries like Ireland lost their entire sugar beet industry, together with a valuable break crop.

Hemp (*Cannabis sativa* L.) is one of the oldest crops in the world, traditionally grown for its long bast fibre although it can be grown for short fibre also (Karus, 2002). Hemp bast fibre was the principal fibre used for maritime ropes and sails for centuries (Dempsey, 1975). Additionally, cannabinoids from hemp seed have been used for medicinal, spiritual and recreational purposes (Van der Werf et al., 1996). Hemp has lost its importance as a raw material for cordage and textile materials, being replaced by cotton and synthetic fibres (Meijer et al., 1995). However, there has been renewed interest in hemp recently as an insulation material as well as a feedstock for specialist paper, and 15,000 ha are currently grown in Europe (Hobson, 2009). Hemp is an excellent break crop as its extensive root system improves soil structure. Subsequent crops have less weed pressure, and yield increases of 10–20% have been shown in winter wheat crops grown after hemp (Bosca and Karus, 1997). It has been demonstrated that hemp can produce high annual yields of biomass (10 t/ha) in Ireland with no agrochemical input and with modest fertilizer input (Crowley, 2001). Van der Werf et al. (1996) reported that Hemp was capable of annual yields of over 17 t of stem dry matter per hectare, while average stem dry matter yields of 11 t per hectare across Europe were reported by Struik et al. (2000), and stem yields of up to 13.6 t of dry matter per hectare (t DM/ha) were reported by Meijer et al. (1995). More recently, Prade et al. (2011) demonstrated that hemp grown for energy could provide yields of 14.4 t DM/ha when harvested in the Autumn and 9.9 t DM/ha when harvested in the spring. Hemp biomass has good combustion properties and could be used to generate either heat or electricity (Rice, 2008). Hemp thus offers the combined potential of an effective break crop and an efficient energy crop, offering farmers the possibility of exploiting new markets in bio-heat and electricity without committing their land for 15–20 years. Work in Sweden has demonstrated the high potential for hemp as a feedstock for the production of solid biofuels or for the production of biogas in anaerobic digestors (Prade et al., 2011; Kreuger et al., 2011). But how does hemp compare with other annual energy crops and with perennial bioenergy crops, economically and as a strategy to mitigate greenhouse gas emissions? The primary objective of this study was to answer that question.

2. Methodology

2.1. Scope, aims and boundaries

Hemp was compared with two annual bioenergy crops, sugar beet and oilseed rape, and two perennial bioenergy crops, willow and Miscanthus, using Life Cycle Assessment (LCA) and Net Present Value (NPV) economic assessment. The study was conducted using Irish data, and results then extrapolated up to the European scale to explore wider implications.

The reference systems used for both the life cycle assessment and the economic analyses were: one hectare over a time period of 21 years at the farm level (annualised); boiler heating energy supply chains for biomass pellets and oil. Functional units were kW h net energy content in processed fuels (pellets ready for use in boilers) were compared with an equivalent displaced net energy content in gas oil and related back to land area. The systems boundary for the LCA was the entire fuel chain, beginning with agricultural input suppliers (e.g. fertiliser manufacture) and ending with final combustion in place of fossil fuels. Hemp, Miscanthus and willow may be used with minimum processing to generate electricity through cofiring in Ireland's peat power stations, or with minor processing to generate electricity through cofiring in coal power stations or heat in boilers (Styles and Jones, 2007). Meanwhile, sugar beet and OSR require extensive processing to extract ethanol and biodiesel. Distribution was not included in the systems boundary. The systems boundary for the economic analyses was the farm enterprise; i.e. the net margin for farm operations was calculated. Simplified economic comparisons excluding subsidies were made in relation to crude oil displacement.

2.2. Yield estimates

When comparing crop environmental and economic performance, estimates of yields are critical. A further complication when comparing perennial crops is their expected productive lifetime, and yield profile over that lifetime, which remains somewhat uncertain. Styles and Jones (2007) previously compared Miscanthus grown over 16 years to willow grown over a 23 year cycle. However, there is little long term data to support definite conclusions about the economic life of willow and Miscanthus and it was decided to compare their performance over assumed productive lifespans of 17, 21 and 25 years respectively. Hemp could be grown in the same field over this period or more typically in different fields as part of a rotation, taking advantage of the benefits of hemp as a break crop. All three crops were considered to have similar yield potential in Ireland. Crowley (2001) reported hemp stem yields up to 14 t DM/ha in Ireland while Van der Werf et al. (1996) reported stem dry matter yields up to 17.1 t DM/ha in the Netherlands. Miscanthus yields greater than 15 t DM/ha in Cashel, Co. Tipperary were reported by Clifton-Brown et al. (2007) and 17.5 t DM/ha were reported by Riche (2005). Willow yields of up to 44.6 t DM/ha for certain varieties in a three year cycle (14.9 t DM/ha/annum) have been reported (DEFRA, 2007) in the UK. The yield of all crops, however, is subject to interannual variation and average yields are invariably lower than peak yields and reflect both good and bad years.

The yield of all crops varies according to meteorological conditions, agronomic practices and soil type. Consequently, each crop was considered across a range of four yield levels which were considered representative of the potential yield range of that crop; a low yield, two mid-level yields and a high yield. Fertiliser application rates affect yields, but are also determined in response to past and expected yields based on yield-response curves. Therefore, low and high fertilization rates were assumed for low and high yields while a mid-range fertilization strategy was assumed for the two mid range yields.

Perennial energy crops exhibit a yield building phase followed by a more stable mature phase. Clifton-Brown et al. (2007) reported average Miscanthus yields of 9 t of dry matter per hectare which reflected both the yield building phase of the crop as well as interannual variability during the mature phase. In this study, we assumed that perennial energy crops also have a third phase characterised by yield decline which precedes a decision to renew or replace the crop. In contrast, annual energy crops such as hemp exhibit their full yield potential in the year of sowing subject to the limitations of soil, management and season and are not expected to exhibit a yield decline phase particularly when grown in a rotation. In order to treat the three crops on an equal basis, four yield scenarios were defined for each crop with mature

Table 1
Biomass yields (t DM/ha) from Hemp, SRC and Miscanthus over a twenty one year productive life cycle.

Year	Hemp				SRC				Miscanthus			
	8	10	12	14	8	10	12	14	8	10	12	14
1	8	10	12	14	0	0	0	0	0	0	0	0
2	8	10	12	14	5.3	6.6	8	9.2	0.9	1.9	2.9	3.9
3	8	10	12	14	5.3	6.6	8	9.2	5.8	6.8	7.8	8.8
4	8	10	12	14	8	10	12	14	8	10	12	14
5	8	10	12	14	8	10	12	14	8	10	12	14
6	8	10	12	14	8	10	12	14	8	10	12	14
7	8	10	12	14	8	10	12	14	8	10	12	14
8	8	10	12	14	8	10	12	14	8	10	12	14
9	8	10	12	14	8	10	12	14	8	10	12	14
10	8	10	12	14	8	10	12	14	8	10	12	14
11	8	10	12	14	8	10	12	14	8	10	12	14
12	8	10	12	14	8	10	12	14	8	10	12	14
13	8	10	12	14	8	10	12	14	8	10	12	14
14	8	10	12	14	8	10	12	14	8	10	12	14
15	8	10	12	14	8	10	12	14	8	10	12	14
16	8	10	12	14	8	10	12	14	8	10	12	14
17	8	10	12	14	8	10	12	14	8	10	12	14
18	8	10	12	14	7.2	9	10.8	12.6	7.6	9.5	11.4	13.3
19	8	10	12	14	7.2	9	10.8	12.6	7.2	9	10.8	12.6
20	8	10	12	14	6.5	8.1	9.7	11.34	6.8	8.6	10.3	12.0
21	8	10	12	14	6.5	8.1	9.7	11.34	6.5	8.1	9.8	11.4
Yield	8	10	12	14	7.1	8.92	10.7	12.5	7.0	8.8	10.5	12.3

yields of 8, 10, 12 and 14 t DM/ha (Table 1). The yield building phase of Miscanthus was modelled according to the results of the TOPGRASS experiment (Riche, 2005) in which Miscanthus was grown at a diverse range of sites in the United Kingdom. For willow, a two year cycle was assumed with yields from the first harvest (year 3) assumed to be two thirds of subsequent harvests (Dawson, 2007). Yields of both Miscanthus and willow in a 21 year rotation were assumed to drop by 5% per year after year 17 as the end of the economic life of the crops approached. Similarly, yields in 17 year and 25 year rotations were assumed to drop by 5% per year after year 13 and year 21, respectively.

Inputs for each crop are described below and follow standard agronomic practice. The most significant input in all cases is fertilizer and a range of nutrient application rates (low, mid and high) was assumed for each crop. The range of nutrient application rates was obtained from the literature which suggested that the nutrient requirements of Miscanthus were lower than those of willow which in turn were lower than those of hemp. Two sources of nutrient were considered, mineral fertilizers and organic fertilizers. The latter could be applied in the form of farm yard manure, slurry or sewage sludge.

2.3. *Hemp*

It was assumed that Hemp would be grown on tillage farms as a break crop. Agronomic operations were assumed to comprise ploughing, tilling, sowing, fertilization, rolling and harvesting. Crowley (2001) established that hemp could be grown in Ireland without the aid of agrochemicals and that a low seeding rate (30 kg/ha) could be used for biomass production where fibre quality is not important. Nitrogen fertilizer is the principal input both in terms of cost and energy input. In France, an optimum nitrogen fertilization rate of 120 kg N/ha is recommended (Institut technique du chanvre (2007)) while trials carried out in 2008, 2009 and 2010 on different sites in Ireland using three different varieties demonstrated that the response curve to nitrogen starts to reach a plateau at 90 kg N/ha with no response expected after 150 kg N/ha and an optimum economic response expected at 120 kg N/ha. (Finnan and Burke, 2013). Therefore, it was decided to use N fertilization rates for hemp which varied between 90 kg N/ha and 150 kg N/ha with a mid-point of 120 kg N/ha. The most common method of harvesting hemp in the UK and on the continent is to mow the crop into 60 cm lengths and leave it to dry in a swarthless medium before windrowing and baling. In this study, harvesting was assumed to consist of these three operations.

2.4. *Sugar beet*

It was assumed the sugar beet would be grown on tillage farms as a break crop. Agronomic operations comprised ploughing, tilling, sowing, rolling, fertilization, spraying and harvesting. Some data specific to sugar beet were taken from Kuesters and Lammel (1999) who generated an LCA for sugar beet systems in Europe. All sugar beet crops were assumed to receive two herbicides, an insecticide and a fungicide during the growing season. Nitrogen fertilization of sugar beet is limited to a maximum rate of 195 kg N/ha by Statutory Instrument No 610 of 2010 (Good Agricultural Practice for the Protection of Waters Regulations). A fertilizer use survey conducted in 2000 showed that sugar beet crops in Ireland received an average of 160 kg N/ha, 43 kg P/ha and 157 kg K/ha (Coulter et al., 2002). It was therefore decided to use three levels of nitrogen application in this study, a low application of 140 kg N/ha, a mid-point application of 165 kg N/ha and a high application of 190 kg N/ha. Corresponding levels of Phosphorus and Potassium were assumed to be applied following the ratio 1:0.4:1.8 (N:P:K) following nutrient advice for sugar beet crops (Coulter and Lalor, 2008). Additionally, crops were assumed to receive 20 kg S/ha and 3 kg B/ha (Coulter and Lalor, 2008). Annual average fresh yields of clean sugar beet were provided by the Central Statistics Office (www.cso.ie) up until 2005. Yields over the period 2000 until 2005 ranged from 42 t/ha to 60 t/ha. It was assumed that present day yields would be somewhat higher due to improvements in varieties and agronomic practices. Consequently, in this study, the yield range used was from 40 t/ha to 70 t/ha. After harvesting, sugar beet was assumed to be transported to a processing plant where bioethanol was produced after cleaning, shredding, diffusion, pasteurisation, fermentation and distillation. Energy use and GHG emissions during transport and processing were taken from Cannell (2003).

2.5. *Winter oilseed rape*

It was assumed that winter oilseed rape would be grown on farms as a break crop. Agronomic operations were assumed to consist of ploughing, tilling, sowing, rolling, spraying, applying fertilizer and harvesting. Seed rates, pesticide inputs and the timings of pesticide and fertilizer applications were taken from Hackett et al. (2006). It was assumed that all crops received an autumn herbicide, two sprays of fungicide/insecticide, one spray of boron and a desiccant spray prior to harvest. Nitrogen fertilization of winter oilseed rape is limited to a maximum rate of 225 kg.

N/ha by Statutory Instrument No 610 of 2010 (Good Agricultural Practice for the Protection of Waters Regulations). Fertilizer use data on winter oilseed rape is not available. It was therefore decided to use three levels of nitrogen application in this study, a low application of 140 kg N/ha, a mid-point application of 180 kg N/ha and a high application of 220 kg N/ha, these levels correspond to the nitrogen recommendations of Hackett et al. (2006). The corresponding rates of phosphorus and potassium recommended by Hackett et al. (2006) were also used. While the central statistics office publishes annual data on oilseed rape yields, the yields are an average of those obtained from winter oilseed rape and spring oilseed rape. Annual harvest reports (unpublished data) give oilseed rape yields ranging from 3.1 t/ha to 4.5 t/ha while Teagasc economic figures for winter oilseed rape provide yield ranges of between 4 t/ha and 6 t/ha. In this study, we used a yield range from 3 t/ha to 6 t/ha. After harvest, oilseed was transported to a processing plant where biodiesel was produced after drying, solvent extraction, refining and esterification. Energy use and GHG emissions during transport and processing were taken from Cannell (2003). After harvest, it was assumed that the oilseed rape straw was collected and baled for energy use, displacing oil, representing nearly complete use of biomass in a manner comparable with energy crop biomass use. Straw yields were taken from Cannell (2003). The calorific value of rape straw was taken from Keppel (2010).

2.6. *Miscanthus*

The first stage of ground preparation for Miscanthus cultivation includes herbicide application followed by subsoiling and ploughing. Rhizomes are planted in the spring following rotavation, ridging and pick-up of 3 year old Miscanthus rhizomes where 1 ha supplied rhizomes to plant 10 ha at 20,000 rhizomes ha^{-1} at a total energy intensity of 4000 MJ/ha (Bullard and Metcalf, 2001). Herbicide application was assumed to consist of two pre-planting applications, one application in each of the first three years and thereafter every two years, two herbicide applications were assumed to be necessary to remove the crop. It was assumed that no fertilizer was used in the first two years nor in the last year. N requirements for Miscanthus were defined by Plunkett (2010) to vary between 30 kg N/ha and 100 kg N/ha depending on soil nutrient status. In contrast, Clifton-Brown et al. (2007) suggested that nitrogen offtakes from a Miscanthus crop grown on former grassland in Co. Tipperary could be met by a combination of soil reserves and atmospheric deposition. For this study, we assumed that nitrogen fertilization was necessary to replace crop offtakes and that nitrogen fertilization rates ranged from 50 kg N/ha to 100 kg N/ha with a mid-point of 75 kg N/ha. The different fertilizer rates correspond to the defined levels of mature yield and consequently to different levels of offtake. At harvest, it was assumed that Miscanthus was mowed and then baled.

2.7. *Short rotation coppice willow*

It was assumed that willow planting is preceded by two herbicide applications, subsoiling, ploughing and tilling. Coppicing (cut-back) in year 1 and each subsequent harvest with the exception of the last harvest is followed by a herbicide application and by fertilization. The last harvest is succeeded by two herbicide applications to kill the crop and ploughing to remove the crop. Yields from the first cropping cycle can be expected to be lower than subsequent cycles because of incomplete site capture before yields reach a plateau with normal variation due to prevailing weather conditions (Dawson, 2007). The yield from the first harvest was taken to be 2/3 of mature yield. After year 17, yields were assumed to decline at 5% per annum for the last four years of the plantation life preceding a decision by the farmer to remove the willow plantation. Fertilization rates up to 120–150 kg nitrogen, 15–40 kg phosphorus and 40 kg potassium per hectare per year have been suggested by Dawson, 2007. Plunkett (2010) suggested nutrient application rates of 40–130 kg N/ha/annum, 0–34 kg P/ha/annum and 0–155 kg K/ha/annum depending on the nutrient levels in the soil. For this study, it was assumed that fertilization of willow is necessary to replace crop offtakes and that nitrogen fertilization rates ranged from 50 kg N/ha/annum to 130 kg N/ha/annum with a mid-point of 90 kg N/ha/annum. The different fertilizer rates correspond to the defined levels of mature yield and consequently to different levels of nutrient offtake. Herbicide application was assumed to comprise of two pre-planting applications, followed by a post cut-back application and an application after each harvest, one additional application was considered necessary to remove the crop. There are two methods of harvesting willow; the crop can be cut and chipped in one operation after which the chips need to be dried immediately. Alternatively, the crop can be cut as whole stems and left to season before chipping (Dawson, 2007). We assumed that willow would be harvested by the latter method to avoid the cost of chip drying.

2.8. *Energy use and GHG emissions*

In the first instance, it was necessary to construct average farm models representing each system, following the example of Casey and Holden (2004) and based on Styles and Jones (2007). All relevant inputs to the system and induced processes (e.g. soil N_2O emissions) were then considered in a life cycle inventory up to the point of the farm gate. All major inputs and sinks of the major greenhouse gases (GHGs), CO_2, CH_4 and N_2O were considered. Inventory mass balances were summed and converted into a final Global Warming Potential (GWP) expressed as kg CO_2eq. considered over a 100 year timescale, according to IPCC (2007) guidelines ($CO_2=1$, $CH_4=23$, $N_2O=296$) as used in the energy crop LCA model reported in Styles and Jones (2007). Although more recent GWP_{100} values were published in IPCC (2007) (25 for CH_4 and 298 for N_2O), the model was run with the older values as CH_4 is a minor component of GHG emissions from the arable systems under study, and the difference for N_2O is insignificant, especially when considered against other sources of uncertainty such as soil emission factors. LCA outputs were calculated and expressed as kg CO_2eq./ha of land and per year, averaged over 21 years (the estimated lifetime of Miscanthus and willow plantations).

Energy use was divided according to two categories of activities; those which primarily used diesel and those which primarily used electricity. A lower heating value of 35.9 MJ/kg was applied (Dalgaard et al., 2001) and diesel lifecycle GHG emissions were calculated according to Flessa et al. (2002) including upstream extraction and processing emissions. Lubrication oil emissions were calculated as 5% of farm machinery diesel emissions (Dalgaard et al., 2001). Greenhouse gas production from electricity usage was calculated using the 2004 GHG intensity of delivered electricity in Ireland (0.173 kg/CO_2eq./MJ/e) after conversion of primary energy requirement values (where literature values reported as such) to delivered electricity based on an efficiency factor of 0.406 (Howley et al., 2006). Indirect emissions associated with agricultural machinery production and maintenance were assumed to be proportional to fuel consumption following the method of Dalgaard et al. (2001). Fertilizer manufacturing, packaging and transport energy intensities of 79.6, 34.5 and 10.5 MJ/kg for N, P, K and S were used to which were added manufacturing N_2O emissions of 9.63 g/kg N (Elsayed et al., 2003). Combined manufacturing and calcification emissions quoted by Elsayed et al. (2003) were divided into manufacturing and soil emissions based on an energy requirement of 6.43 MJ/kg. Soil emissions were calculated as per Ireland's National Inventory Report (McGettigan et al., 2006). Herbicide energy contents were obtained by multiplying the energy content per active unit of herbicide (Dalgaard et al., 2001) by the average active ingredient/ha for herbicides approved for willow and Miscanthus, active/ingredient/ha in oilseed rape herbicides and active ingredient per hectare in beet herbicides. Similarly, fungicide and insecticide energy contents were obtained by multiplying the average active ingredient per hectare for approved fungicides and pesticides by the energy content per active ingredient of herbicide as given by Dalgaard et al. (2001).

2.9. Below ground carbon storage

Carbon is stored under ground in roots and rhizomes, and following decomposition some of this carbon may remain sequestered in the soil for long periods of time, so that increasing quantities of this fraction in soils correspond with long-term removal from the atmosphere. The quantity of below ground biomass was assumed to be directly related to the quantity of above ground biomass, and thus varied with yield scenarios. There is considerable debate about the quantity of carbon sequestered in the soil under different circumstances. Soil carbon accumulation will depend on several factors such as existing soil carbon content, soil structure and meteorological conditions.

Previous studies have shown that the introduction of rotation into an arable system can lead to increases in soil carbon (West and Post, 2002). Hemp grows via a substantial tap root (Amaducci et al., 2008) which is left in the soil after harvest. However, in an annual arable system it is likely that most of the soil carbon would be mineralised and oxidised following tillage operations, and therefore not contribute to long-term sequestration. In the absence of data on the accumulation of carbon in soil systems following hemp cultivation, it was decided to assume that there was no net gain in carbon in soils where hemp was included in a rotation, as per Similarly, it was assumed that there would be no net increase or decrease in soil carbon after sugar beet or winter oilseed rape are cultivated; i.e. that soil carbon in the tillage soils in which these crops are routinely grown is in equilibrium.

Arable soils typically have a low carbon content and it is generally accepted that conversion to perennial crops will result in an increase in soil carbon content. However, the conversion of grassland to perennial crops is more complex and there is uncertainty as to whether the conversion of grassland to perennial biomass crops will lead to any increase in soil carbon. Clifton-Brown et al. (2007) could not show any significant difference between the soil carbon content under a long term Miscanthus crop and an adjacent pasture. For this study, two scenarios were considered for below ground carbon storage for perennial crops, grassland and arable. It was assumed that there would be no increase in soil carbon when grasslands were converted to perennial energy crops but that soil carbon would increase if perennial energy crops were sown on arable land. A sequestration rate of 0.6 t C/ha/annum was used for Miscanthus (Clifton-Brown et al., 2007) while a sequestration rate of 0.5 t C/ha/annum was used for willow (Matthews and Grogan, 2001), under mid yield estimates. These sequestration rates were assumed to vary in direct proportion with yield.

2.10. Carbon mitigation

Carbon sequestration was subtracted from cultivation emissions to calculate net cultivation emissions. Gross GHG abatement from the substitution of fuels for heat and electricity production was based on the assumption that the fuel replaced would be light fuel oil. The calculation was performed based on a lifecycle GHG burden of 0.087 kg/CO_2eq./MJ diesel oil (Elsayed et al., 2003). Gross GHG abatement from the replacement of petrol and diesel by bioethanol and biodiesel was also calculated based on emission factors from Elsayed et al. (2003)—i.e. 0.081 and 0.087 kg/CO_2eq./MJ petrol and diesel, respectively. Processing and transport emissions arising from the use of Miscanthus, SRC, hemp and OSR straw biomass for heating were calculated from factors presented in Gustavsson and Karlsson (2002). Pelleting energy was assumed to be provided as electricity, and the Irish GHG emission factor described above was applied. Heating boiler efficiency for biomass was assumed to be 85%, compared with 90% for oil boilers. Bioethanol and biodiesel processing energy and emission factors were taken from Elsayed et al. (2003). Net carbon mitigation was calculated on a per hectare basis for each energy crop as gross GHG avoidance by fuel substitution minus cultivation and processing emissions.

Substantial land areas within the EU are used for liquid biofuel production at present, the two principal crops grown are oilseed rape for biodiesel production and sugar beet for bioethanol production. Hemp could be grown on some of this land to produce feedstock for heat and electricity production. The net GHG abatement obtained from replacing 25% of the oilseed rape and 25% of sugar beet (land area basis) with hemp was calculated. Sugar beet and oilseed rape land areas in the EU together with the average yields of these crops were obtained from FAOSTAT (2009), data was the most recently available and was used for calculations. 25% of oilseed rape area amounted to 1620,336 ha while 25% of sugar beet area amounted to 373,085 ha. GHG abatement from these areas at present is potentially achieved through the production of bioethanol from sugar beet and the production of biodiesel and straw feedstock from oilseed rape. Average EU yields (3.3 t/ha for oilseed rape and 69.5 t/ha for sugar beet) were used to calculate GHG abatement from these areas. GHG abatement from the production of hemp in these land areas was calculated for yields of 8 t/ha to 14 t/ha. Net additional GHG abatement was calculated as (GHG abatement from hemp—GHG abatement from oilseed rape or sugar beet).

2.11. Economic analysis

An economic analysis was performed for the low, middle and high yielding scenarios for each crop. Establishment costs for willow and Miscanthus were taken from current charges for rhizomes/cuttings as well as from current contractors charges. The cost of hemp seed (180/ha) was obtained from a quotation from Co-operative Centrale des Producteurs de Semences de Chanvre, the principle producer of hemp seed in Europe assuming a seeding rate of 30 kg/ha (Crowley, 2001). The cost of field operations and herbicides were taken from figures for crop costs and returns (O'Mahony, 2010). The cost of fertilizer was taken from figures from the central statistics office (CSO, 2010) and adjusted according to inflation. Organic fertilizers could come either from manure or slurry generated on the farm or from organic wastes such as sewage sludge. Some studies have assumed a gate fee for organic wastes. However, we assumed that the costs of transportation and spreading would be borne by the waste company but that the farmer would not receive any direct income from the spreading of sewage sludge on his land.

Net margins from hemp production were also compared to those from winter oilseed rape and sugar beet. As gross margins vary from year to year, it was decided to calculate the gross margins for oilseed rape and sugar beet from an average of the most recent three years, 2009, 2010 and 2011. Gross margins for these crops over this three year period were obtained from Teagasc (O'Mahony, 2009, 2010; and O'Donovan, 2011) and compared to gross margins for hemp calculated above. Theoretical net margins from all three annual crops were calculated by assuming that the net energy output per hectare was equivalent to the market price for crude oil containing an equivalent energy content; 0.54/L, excluding all duties, according to the EU energy portal (values updated February 2013).

An economic spreadsheet model, based in Microsoft Excel, was used to evaluate the life cycle economics of the three crops. A net present value approach (NPV) was adopted, similar to that presented by Rosenqvist et al. (1997) in which the three crops were converted to an annual income stream which facilitated a comparative economic analysis. Total costs and returns for the three energy crops were compared over the greatest plantation lifespan of 21 years (willow), calculated as NPV for the year of plantation using a 5% discount rate, annualised and expressed per hectare. For Miscanthus and willow, two alternative economic scenarios were evaluated. The first alternative scenario evaluated the economic returns from both crops without the availability of an establishment grant. The second alternative scenario used an 8% discount rate for all three crops to reflect a higher expected rate of return from the more risk averse farmer.

3. Results

Fig. 1 displays the breakdown of annual GHG emissions arising from the cultivation of one hectare of each of the five energy crops considered, including indirect upstream emissions from the manufacture of agrochemicals and machinery, under mid yield scenarios. Hemp cultivation gives rise to annual GHG emissions of almost 3 t/CO_2 eq., intermediate between Miscanthus and SRC (both approximately 2 t/CO_2 eq./year) and sugar beet and OSR (both approximately 3.5 t/CO_2 eq./year, respectively). In all cases, indirect emissions (primarily fertiliser manufacture) and soil emissions (primarily N_2O stimulated by fertiliser application) dominate. For Miscanthus and SRC planted on tillage land, annualised rates of soil carbon sequestration offset cultivation emissions, resulting in a negative net GHG emission for each hectare planted with Miscanthus. This sequestration effect does not occur when Miscanthus and SRC are planted on grassland. Reducing the productive plantation lifetime for the two perennial energy crops to 17 years increased annualised cultivation GHG emissions by less than four percent, whilst increasing the productive plantation lifetime reduced annualised cultivation emissions by less than three percent (data not shown).

Substituting mineral with organic fertilizers such as sewage sludge to supply crop nutrient demands reduces cultivation emissions by between 0.4 and 1.5 t/CO_2 eq./ha/year (Fig. 2). This effect arises through the avoidance of upstream fertiliser manufacture emissions, and therefore is proportionate to fertiliser application rates across the energy crops-resulting in the largest cultivation emission reductions for hemp and the smallest for Miscanthus. Nonetheless, mid-yield cultivation emissions for hemp remain 25% and 19% higher than for Miscanthus and SRC planted on grassland, respectively (Fig. 2). If organic fertilisers are applied to the. two perennial energy crops planted on arable land, their cultivation acts as a net GHG sink over plantation lifetimes, sequestering between 0.5 (SRC) and 0.9 (Miscanthus) t/CO_2 eq./ha/year.

Varying yield estimates changed the amount of fertiliser and harvesting emissions, and also the amount of soil carbon sequestration when the perennial crops are planted on arable land. Excluding soil sequestration effects for the perennial crops, low yields resulted in cultivation emission reductions of between 8% and 25% across all crops, whilst high yields led to cultivation emission increases of between 11% and 25% across all crops (Fig. 2). For the perennial crops planted on arable land, additional soil carbon sequestration under high yields more than offset GHG emissions arising from additional fertiliser applications, resulting in higher net CO_2 sequestration under high yielding crops (Fig. 2).

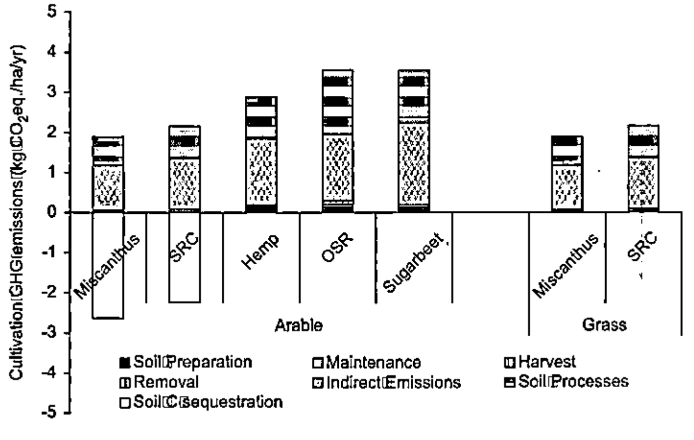

Fig. 1. Total GHG emissions arising from the cultivation of one hectare of the different energy crops, including carbon sequestration, for mid-yield scenarios.

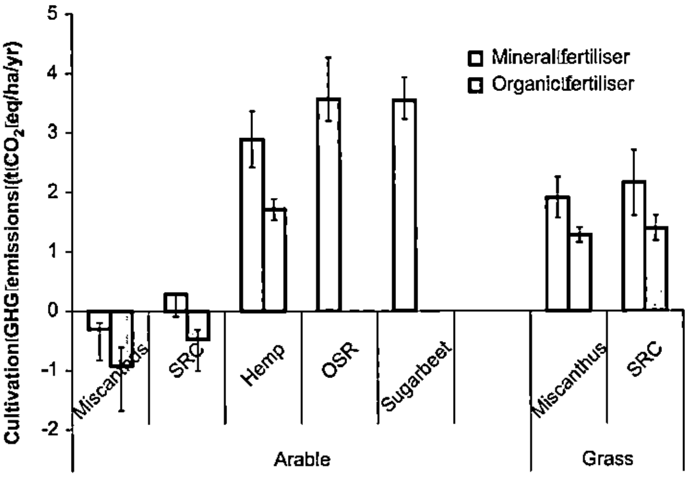

Fig. 2. Variation in net cultivation GHG emissions arising across the range of. yield estimates for each crop (error bars), and depending on either mineral or organic fertilizer application for Miscanthus, SRC and hemp.

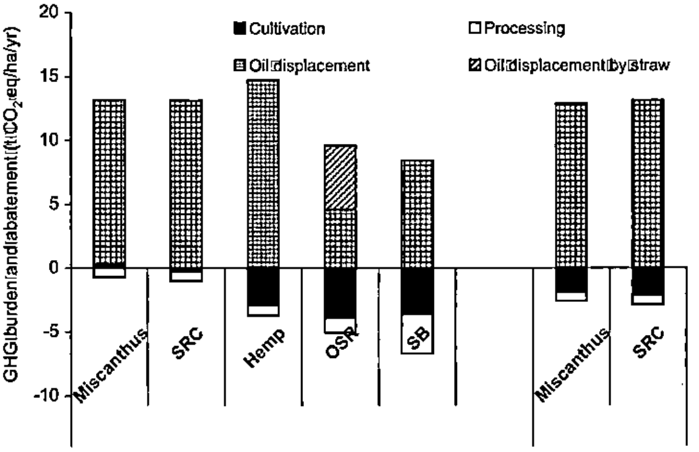

Fig. 3. Breakdown of GHG avoidance achieved by different energy crops, based on mid yield estimates.

3.1. Bioenergy chain GHG and energy balance

For mid yield estimates of hemp, Miscanthus and SRC, cultivation emissions equate to 20%, 15% and 16%, respectively, of the gross emissions avoided through displacement of oil (Fig. 3). Net cultivation carbon sequestration for Miscanthus planted on arable land supplements GHG avoidance from oil substitution by 2.4% at the mid yield estimate, whilst net cultivation emissions from SRC planted on arable land offset oil displacement GHG avoidance by 2.2% (Fig. 3). For OSR and sugar beet, cultivation emissions offset gross emission avoidance through heating and transport oil substitution by 41% and 43%, respectively, and processing emissions offset gross emissions avoidance by a further 12% and 37%, respectively. By contrast for hemp and the perennial energy crops, processing and transport GHG emissions equate to less than 5.5% of the gross emissions avoided through oil substitution (Fig. 3).

Consequently, the net GHG abatement attributable to the hemp energy chain under the mid yield estimate, 11 t/CO_2eq./ha/year, is 140% greater than for OSR energy chains and 540% greater than for the sugar beet ethanol fuel chain, expressed per hectare of land planted (Fig. 4). Net GHG abatement attributable to the hemp energy chain is slightly lower than for the Miscanthus and SRC energy chains when the latter crops are planted on arable land, but higher than for Miscanthus and SRC energy chains when those crops are planted on grassland (Fig. 4). Varying yield estimates has a strong effect on net GHG avoidance, but does not effect the comparative performance of the different crops. For hemp, the yield range of 8 to 14 t per hectare per year is associated with a range of net GHG abatement from between 8.7 and 16.1 t/CO_2eq. per hectare per year. Reducing cultivation emissions through use of organic fertilisers (Fig. 2) could further increase net GHG abatement, by up to 1.5 t/CO_2eq. per hectare per year.

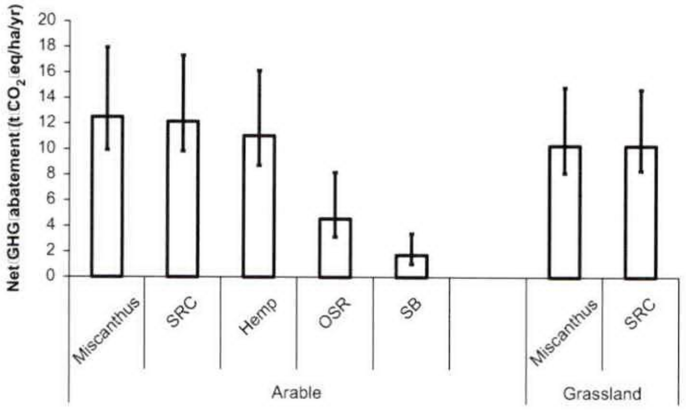

Fig. 4. Variation in net GHG avoidance across the range of yield estimates for each crop (error bars).

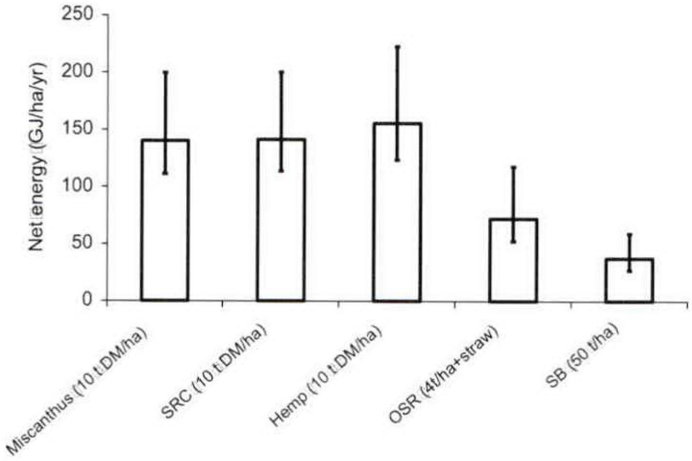

Fig. 5. Useful energy balance of fuel chains for the different crops.

Regarding the energy balance, the hemp energy chain achieves the highest net useful energy yield of 156 GJ per hectare per year at mid yield, varying from 124 GJ to 223 GJ per hectare per year across yield estimates (Fig. 5). The perennial energy crops achieve slightly lower energy yields of 140 GJ per hectare per year under mid yields. OSR and sugar beet achieve net energy yields of 72 GJ and 37 GJ per hectare per year, respectively, under mid yields (ranges 53–118 GJ/ha/year and 27–59 GJ/ha/year) (Fig. 5).

3.2. Economic analysis

The biomass price needed to cover the costs of hemp production was 98.1/DM t when mineral fertilizers were used and 61.6/DM t when organic manures were used for fertilizer.

Annualised, discounted profit margins at a discount rate of 5% are shown in Table 2 for biomass prices ranging from 80/DM t to 140/DM t, with and without the availability of an establishment grant and using either inorganic fertilizers or organic fertilizers. Profits from Miscanthus were greater than those from the SRC. The difference between Miscanthus and SRC ranged from 71 to 194 when mineral fertilizers were used and 56 to 121 when organic manures were used. This difference was primarily a reflection of the higher costs of harvesting willow.

The availability of a grant increased annualised discounted profit margins for Miscanthus by 121 and for willow by 116. The effect on profit of replacing mineral fertilizer with organic fertilizers was a reflection of the amount of nutrients required by the crop. Consequently, the greatest benefit was for hemp, followed by willow and Miscanthus, respectively. Replacing mineral fertilizer with organic fertilizer improved the annualised, discounted, profit margin for hemp by between 285 and 294/annum (mid-point values) depending on the price of biomass.

Table 2
Economic comparison between Hemp, Miscanthus and short rotation coppice willow with and without the availability of an establishment grant and across a range of prices and using either mineral fertilizer (MF) or organic fertilizers (OF) as a source of nutrition. Discount rate equals 5%.

Grant	Nutrition	Price per tonne	Miscanthus				Hemp				SRC			
			8	10	12	14	8	10	12	14	8	10	12	14
Yield (t DM/ha/annum)														
Yes	MF	80	25	58	157	178	−163	−140	−16	7	−55	−80	20	−6
Yes	MF	100	123	181	305	361	−39	15	169	223	45	44	170	169
Yes	MF	120	221	305	454	538	84	169	354	439	145	169	319	344
Yes	MF	140	320	428	602	697	208	323	539	655	245	294	469	519
Yes	OF	80	104	177	276	386	54	145	256	347	40	91	191	291
Yes	OF	100	202	300	425	536	181	302	441	563	140	216	341	417
Yes	OF	120	300	424	573	713	307	460	626	779	240	341	491	592
Yes	OF	140	399	547	721	869	434	617	811	995	340	466	641	767
No	MF	80	−96	−63	36	57	−163	−140	−16	7	−171	−196	−96	−122
No	MF	100	2	60	184	230	−39	15	169	223	−71	−71	54	54
No	MF	120	100	184	333	403	84	169	354	439	29	54	204	228
No	MF	140	320	428	602	697	208	323	539	655	245	294	469	519
No	OF	80	−17	56	156	229	54	145	256	347	−76	−25	76	127
No	OF	100	81	179	304	402	181	302	441	563	24	100	226	302
No	OF	120	180	303	452	575	307	460	626	779	124	225	376	477
No	OF	140	399	547	721	869	434	617	811	995	340	466	641	767

Table 3
Economic comparison between Hemp, Miscanthus and short rotation coppice willow with and without the availability of an establishment grant and across a range of prices and using either mineral fertilizer (MF) or organic fertilizers (OF) as a source of nutrition. Discount rate equals 8%.

Grant	Nutrition	Price per tonne	Miscanthus				Hemp				SRC			
			8	10	12	14	8	10	12	14	8	10	12	14
Yield (t DM/ha/annum)														
Yes	MF	80	−13	12	86	101	−127	−109	−13	5	−70	−90	−17	−37
Yes	MF	100	60	103	196	230	−31	11	132	174	4	2	94	92
Yes	MF	120	133	195	306	358	66	132	276	342	78	94	205	221
Yes	MF	140	206	286	416	487	162	252	421	511	151	186	315	350
Yes	OF	80	46	100	174	229	42	113	200	271	2	40	114	151
Yes	OF	100	119	192	284	357	141	236	345	440	76	132	225	281
Yes	OF	120	192	283	394	486	240	359	489	608	150	224	335	410
Yes	OF	140	265	375	504	614	338	482	634	777	224	316	446	539
No	MF	80	−132	−107	−34	−18	−127	−109	−13	5	−184	−205	−131	−151
No	MF	100	−59	−16	76	110	−31	11	132	174	−110	−112	−20	−22
No	MF	120	14	76	186	239	66	132	276	342	−20	−36	91	107
No	MF	140	87	167	296	367	162	252	421	511	37	72	201	236
No	OF	80	−73	−19	55	110	42	113	200	271	−112	−74	0	37
No	OF	100	0	73	165	238	141	236	345	440	−38	18	110	167
No	OF	120	72	164	275	366	240	359	489	608	36	110	221	296
No	OF	140	145	255	385	495	338	482	634	777	109	202	332	425

Table 4
Economic comparison between Hemp, Miscanthus and short rotation coppice willow using mineral fertilizers with the availability of an establishment grant for different productive life cycles and across a range of prices. Discount rate equals 5%.

Productive Life Cycle	Price per tonne	Miscanthus				Hemp				SRC			
		8	10	12	14	8	10	12	14	8	10	12	14
Yield (t DM/ha/annum)													
17 year	80	−4	29	130	232	−173	−149	−17	7	−86	−128	−46	−36
	100	96	155	281	408	−42	16	180	237	17	1	108	144
	120	197	280	433	585	90	180	377	467	119	128	261	323
	140	297	406	584	761	221	344	574	697	222	256	415	502
21 year	80	25	58	157	178	−163	−140	−16	7	−55	−80	20	−6
	100	123	181	305	361	−39	15	169	223	45	44	170	169
	120	221	305	454	538	84	169	354	439	145	169	319	344
	140	320	428	602	697	208	323	539	655	245	294	469	519
25 year	80	42	74	171	267	−153	−132	−15	6	−36	−60	37	12
	100	138	194	314	435	−37	14	159	210	61	61	182	181
	120	233	314	458	603	79	159	334	414	158	182	327	350
	140	329	433	602	771	196	305	508	617	255	302	472	520

Changing to organic manure improved the profitability of Miscanthus by 119/annum and of willow by 171/annum (mid-point values). Increasing the discount rate applied to perennial energy crops from 5% to 8% (Table 3) reduced annual discounted profits per hectare to between 37/ha to 208/ha for Miscanthus and from 5/ha to 182/ha for SRC (mid-point values).

Annualised, discounted profits for hemp at equal mature yields were lower than those from Miscanthus when establishment grants were available and mineral fertilizers were used for crop nutrition at a discount rate of 5% over a productive lifespan of 21 years (Table 2). When mineral fertilizers were replaced with organic fertilizers, profits from hemp exceeded those of Miscanthus at and above a yield of 10 t/ha and a biomass price of 100/t. In the absence of an establishment grant and when mineral fertilizer was used as a source of nutrients, profits from hemp production were almost always lower than those of Miscanthus at equal mature yields. However, when organic fertilizers replaced mineral fertilizers in the absence of establishment grants, profits from hemp production exceeded those from Miscanthus. Profits from hemp production exceeded those from SRC at and above yields of 12 t DM/ha and a biomass price of 120/DM t at equal mature yields and a discount rate of 5%. Profits from hemp production exceeded those of SRC in the absence of establishment grants irrespective of whether mineral fertilizers or organic fertilizers were used.

The discount rate was increased to 8% for all three crops to represent a situation in which more risk averse farmers examined the crops more cautiously before committing to long land investments periods. In this scenario, shown in Table 3, profits from hemp production exceeded those from the two perennial energy crops throughout the range of biomass prices when organic fertilizers were used both with and without the availability of a grant. When mineral fertilizers were used as a source of nutrition and a grant was available, hemp profits exceeded those from SRC at and above a yield of 10 t DM/ha and a biomass price of 100/DM t but were generally lower than those of Miscanthus. In the absence of an establishment grant, profits from hemp exceeded those from both willow and Miscanthus when mineral fertilizers were used.

Gross margins for Miscanthus, SRC and hemp for different perennial energy crop productive life spans when mineral fertilizers were used and establishment grants were available are shown in Table 4. Profits from hemp production were lower than those from Miscanthus production irrespective of the productive lifespan of Miscanthus. Hemp was more profitable than SRC in certain circumstances although hemp became less profitable as the productive

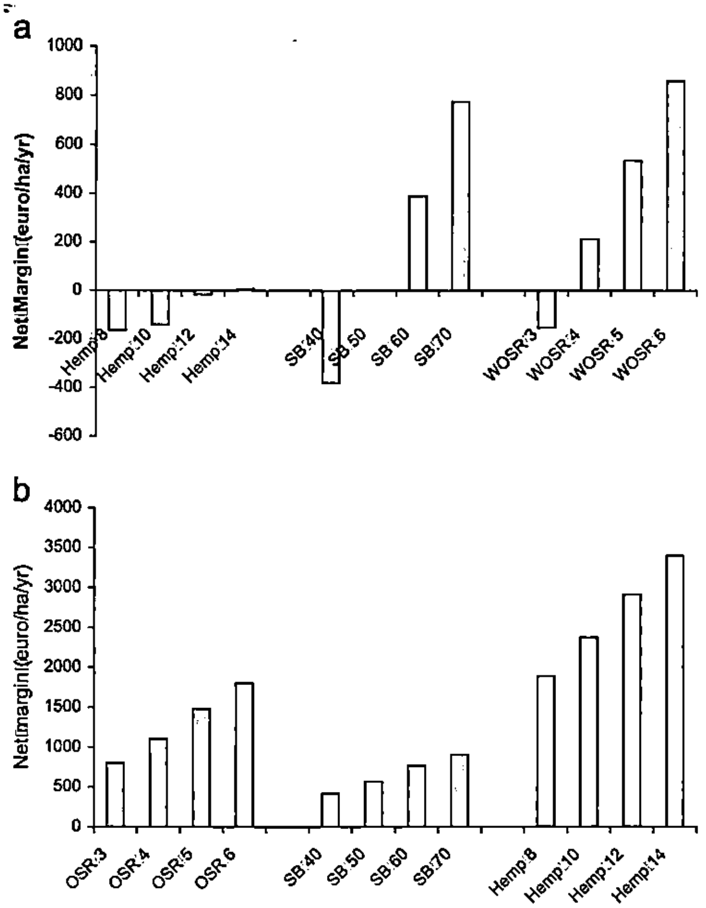

Fig. 6. Net margins of break crops. (a) current prices. Margins for hemp. assume a current price of 80/DM t. Net margins for sugar beet and winter oilseed rape are an average of three years 2009, 2010 and 2011. (b) Converting net energy into oil prices @ 0.54/L oil.

lifespan of SRC increased from 17 to 25 years. Increasing the productive lifespan of Miscanthus and SRC had only a small effect on the gross margins of these crops. The level of mature yield reached by perennial energy crops had the greatest effect on gross margins.

A comparison between the net margins of hemp, sugar beet and oilseed rape are shown in Fig. 6a for different yield levels. Nett margins for hemp assume a current price of 80/DM t. Nett margins for sugar beet and winter oilseed rape are an average of three years 2009, 2010 and 2011. At current biomass prices, net margins for hemp compare unfavourably to both sugar beet and oilseed rape. Calculations of net margins on the basis of the assumption that the energy yield from the three crops is equivalent to the value of the oil replaced is shown in Fig. 6b. In this case, net margins from hemp production greatly exceed those of sugar beet and oilseed rape.

3.3. *Energy security and GHG mitigation at European level*

Extrapolated up to the EU scale, replacing 25% of OSR used to produce transport fuel and heat (OSR straw) with hemp used to substitute heating oil could result in additional GHG avoidance of between 8 and 20 Mt/CO_2eq./year depending on hemp yields, increasing GHG avoidance by between 149% and 362% (Fig. 7). Replacing 25% of sugar beet used to produce ethanol for transport with hemp could result in additional GHG avoidance of between 2 and 5 Mt/CO_2eq./year depending on hemp yields, increasing GHG avoidance by between 154% and 371% (Fig. 7). The picture is similar for net useful energy generation (gross useful energy generated minus all primary energy used in the fuel chain), with the use of hemp generating an additional 112% to 281% useful energy compared with full utilisation of OSR (oil substitutes diesel and straw substitutes heating oil), and an additional 109% to 276% energy compared with sugar beet used to produce bioethanol (Fig. 7).

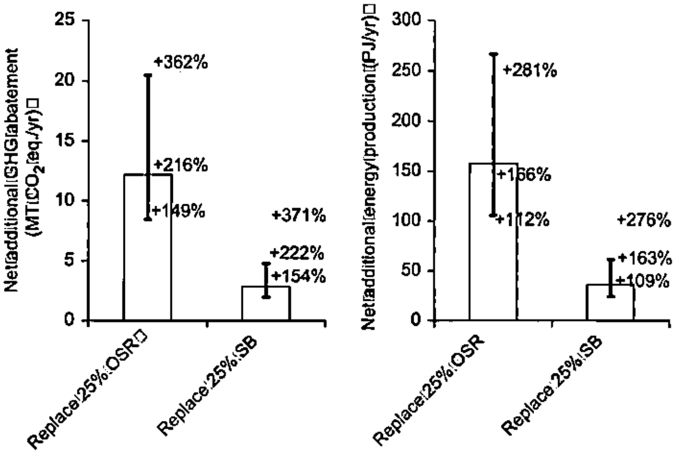

Fig. 7. The net additional GHG avoidance and energy production achievable. by replacing 25% of OSR and 25% of sugar beet grown in the EU with hemp used to substitute heating oil, based on mid yield (columns) and yield ranges (error bars) for hemp.

4. Discussion

4.1. *GHG abatement potential*

This study has demonstrated that the greenhouse gas mitigation potential of hemp grown as an annual break crop on tillage land is similar to perennial energy crops such as Miscanthus and SRC grown on grassland. Of course, these results depend on the assumptions applied in the study, in particular the comparative yields and end use of the biomass. Hemp, Miscanthus and SRC have similar biomass production potential, but their comparative performance depends on local conditions such as climate and especially soil type. The productive lifetimes of perennial energy crops remain somewhat uncertain, in part because it is difficult to predict the stresses which will confront these crops over 15–20 year plantation lifetimes from, for example, drought or pathogens. Dawson (2007) claimed that nine successive harvests are possible from modern varieties of willow grown in mixtures before improvements in breeding alone would make it worthwhile to re-sow, while Bullard and Metcalf (2001) assumed 20 years to be the economic lifetime of a Miscanthus plantation. Some studies have shown a yield decline for Miscanthus after 10 years (Clifton-Brown et al., 2007), although this was without fertilizer application. However, varying plantation lifetimes had little influence on the GHG abatement potential of these perennial crops in this study.

Perennial energy crops are characterised by low inputs for cultivation, and also by their potential to sequester carbon in the soil and in extensive underground biomass (Clifton-Brown et al., 2007; Matthews and Grogan, 2001). This effect is most significant in tillage soils which have low carbon contents. Conversion of grassland to perennial energy crop production is expected to result in an initial loss of stored carbon following initial ploughing and soil preparation. After this initial loss, however, soil carbon reserves are expected to return to a level equal to or greater than that for grassland soils. Thus, in terms of the cultivation GHG balance, the principal advantages of perennial energy crops over annual energy crops are low cultivation emissions and their ability to sequester carbon. Nonetheless, for Miscanthus, SRC and hemp, cultivation emissions (and carbon sequestration) are small in relation to GHG mitigation through fuel substitution, so that hemp compares favourably with both perennial crops in terms of total GHG abatement potential if it is considered that all of these crops have similar yield potential. Furthermore, economic considerations suggest that Miscanthus and SRC are more likely to be grown on grassland soils where any soil carbon sequestration effect will be small.

Traditional annual bioenergy crops such as OSR and sugar beet have higher GHG burdens during cultivation than hemp or perennial energy crops, primarily owing to their higher fertilizer and agrochemical requirements. Sugar beet also requires energy-intensive processing (fermentation and distillation) to extract bioethanol. Consequently, the net GHG abatement potential and net energy balance of these crops is considerably lower than for hemp or the perennial energy crops.

4.2. *Farm economic considerations*

Although not incurring the high establishment costs of willow and Miscanthus, hemp is associated with higher annual costs compared with perennial energy crops owing to annual soil preparation and seed purchase costs, and higher fertiliser requirements. However, the comparative economics of hemp improve in relation to perennial energy crops when nutrient requirements are met by the application of organic manures or sewage sludge, and in the absence of establishment grants for perennial crops. Furthermore, hemp is more appealing to risk averse farmers for whom a higher discount rate should be considered. With an annual energy crop such as hemp, farmers receive full returns in the year of planting, and are free to continue or discontinue with hemp cultivation the following year based on experience. By contrast, a decision to grow perennial energy crops is accompanied by a high initial investment, a waiting period before cash flows become positive, and a commitment of land for a period of 20+ years.

4.3. *A role for hemp in bioenergy strategies*

To enable better like-for-like comparison, and reflecting current energy security concerns, it was assumed that all crops compared in this study would substitute oil. In fact, Miscanthus, SRC and hemp biomass may be more likely to be used for electricity generation through co-firing in coal and peat power stations in Ireland. This end use may require less processing (Styles and Jones, 2007), and lead to greater GHG abatement through the substitution of more carbon intensive fuels. Nonetheless, it is clear from the comparison based on oil substitution that the perennial energy crops and hemp are considerably more efficient feedstocks than OSR and sugar beet. In addition to achieving greater reductions in GHG emissions, the use of hemp could substitute a considerably greater quantity of oil than the use of biodiesel and straw pellets from OSR and bioethanol from sugar beet. The scenarios represent complete use of lignocellulosic biomass for energy (including OSR straw) but do not consider the possible use of sugar beet pulp as an animal feed, which, through allocation within LCA, could improve the comparatively poor energy balance of sugar beet somewhat. Meanwhile, a major criticism directed at the use of annual energy crops to produce biofuels is the detrimental impact this can have on food supply. Additional advantages of hemp compared with OSR and sugar beet are that it is not a food crop and it acts as a relatively low input break crop that can improve soil quality and the yields of subsequent crops. Thus, cultivated within a crop rotation cycle, hemp production can complement, rather than compete with, food production. Perennial crops such as Miscanthus and SRC, or long rotation forestry, are regarded as more sustainable long-term sources of bioenergy than traditional annual energy crops owing to their low inputs and their suitability for cultivation on less productive soils not used for food production. However, these crops are relatively new for farmers, require long commitment periods, and require time to build up yields. A significant advantage of hemp over perennial energy crops is the immediacy of supply offered. Annual energy crops such as hemp can produce high biomass yields immediately without the need to wait until the end of a yield building phase. This is an important advantage in terms of providing a responsive and variable biomass supply to biomass consumers (e.g. power stations), and a relevant aspect for policy makers to consider when contemplating bioenergy strategies. Hemp may be a particularly valuable crop to introduce farmers to bioenergy production and to establish biomass supplies. The shrinkage of the EU sugar sector since 2006 has meant that a lot of tillage land in Europe is without an efficient break crop. Hemp offers a far more efficient alternative to sugar beet and OSR, as a break crop that can be used for bioenergy production and green house gas mitigation. The emphasis on production of transport biofuels within the EU, currently supplied from annual energy crops such as OSR and sugar beet, deters the development of more effective and sustainable bioenergy fuel chains such as the production of heat and electricity from hemp and perennial crops. In particular, the subsidisation of transport biofuel production (e.g. through reduced duties) distorts the market for bioenergy by generating high prices for OSR and sugar beet feedstocks.

References

Amaducci, S., Zatta, A., Raffanini, M., Venturi, G., 2008. Characterisation of hemp (*Cannabis sativa* L.) roots under different growing conditions. Plant and Soil 313, 227–235.

Bosca, I., Karus, M., 1997. The Cultivation of Hemp: Botany, Varieties, Cultivation and Harvesting. Hemptech, Sebastopol, CA95473, California.

Bullard, M., Metcalf, P., 2001. Estimating the Energy Requirements and CO_2 Emissions of the Perennial Grasses Miscanthus, Switchgrass and Reed Canary Grass. Energy Technology Support Unit. Harwell, UK.

Cannell, M.R., 2003. Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass and Bioenergy 24, 97–116.

Casey, J.W., Holden, N., 2004. Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86, 97–114.

Clifton-Brown, J.C., Bruer, J., Jones, M.B., 2007. Carbon mitigation by the energy crop, Miscanthus. Global Change Biology 13, 1–12.

Coulter, B., Murphy, W.E., Culleton, N., Finnerty, E., Connolly, L., 2002. A Survey of Fertilizer use in 2000 for Grassland and Arable Crops. Teagasc, Dublin 2002.

Coulter, B., Lalor, S., 2008. Major and Micro Nutrient Advice for Productive Agricultural Crops. Third ed. ISBN 1 84170 501 2. Teagasc, Johnstown Castle, Wexford. www.teagasc.ie/johnstowncastle/〉.

Crowley, J.G., 2001. The Performance of *Cannabis sativa* (Hemp) as a Fibre Source for Medium Density Fibre Board. Teagasc End of Project Report 4487. ISSBN 1 84170 164 5.

CSO (2010) Agricultural Price Indices, March 2010. Central Statistics Office. Ardee Road, Dublin 6.

Dalgaard, T., Halberg, N., Porter, J.R., 2001. A model of fossil energy use in Danish agriculture used to compare organic and conventional farming. Agriculture, Ecosystems and Environment 87, 51–65.

Dawson, M., 2007. Short Rotation Coppice Willow Best Practice Guidelines. RENEW Project. ISSBN 0948870-07-9.

DEFRA, 2007. Assessing Biomass Miscanthus and Short Rotation Coppice Willow and Poplar Varieties: The Way Forward. Final Report Project NF0435.

Dempsey, J.M., 1975. Hemp. In Fibre Crops, Gainsville. University of Florida Press, USA 46–89.

Elsayed, M.A., Mathews, R., Mortimer, M.D., 2003. Carbon and Energy Options for a Range of Biofuel Options. Sheffield Hallam University 2003.

E.U., 2006. The European sugar sector, a long-term competitive future. http://ec.europa.eu/agriculture/capreform/sugar/infopack_en.pdf〉, (accessed 11/12/2010).

FAOSTAT, 2009. FAOSTAT Agriculture Data, Food and Agriculture Organization of the United Nations. http://apps.fao.org〉, (accessed 1/8/2011).

Finnan, J, Burke, B, 2013. Nitrogen fertilization to optimize the greenhouse gas balance of hemp crops grown for biomass. Global Change Biology Bioenergy. http://dx.doi.org/10.1111/gcbb.12045.

Flessa, H., Ruser, R, Dorsch, P, Kamp, T, Jimenez, M.A., Munch, J.C., 2002. Integrated evaluation of greenhouse gas emissions from two farming systems in southern Germany. Agriculture, Ecosystems and Environment 91, 175–189.

Gustavsson, L., Karlsson, A., 2002, A system perspective on the http://www.sciencedirect.com/science/article/pii/S030142150700376X> -hit192heating of detached houses. Energy Policy, 30, 553–574.

Hackett, R., Dunne, B., Kennedy, T., Forristal, D., Burke, J.I., 2006. Growing Oilseed Rape in Ireland. ISBN 1 84170 455 5. Teagasc, Crops Research Centre, Oak Park, Carlow. www.teagasc.ie/publications/>.

Hobson, J., 2009. Why hemp should be a crop of the future-update! In: Sixth Conference of the European Industrial Hemp Association. Wesseling, Cologne.

Howley, M., O'Leary, F., Gallachoir, B., 2006. Energy in Ireland 1990–2004: trends, issues, forecasts and indicators. SEI Dublin.

Institut Technique, du Chanvre, 2007. Le chanvre industriel. Guide technique. Institut Technique du Chanvre, Technopole de l'Aube en Champagne, Hotel de Bureaux 2, BP601-10901 Troyes.

IPCC, 2001. Radiative forcing of climate change. In: Climate Change 2001: The Scientific Basis (Chap. 6). IPCC. http://www.grida.no/climate/ipcc_tar/wg1/248.htm>.

Karus, M., 2002. European hemp industry 2001: cultivation, processing and product lines. Journal of Industrial Hemp 7, 95–99.

Keppel, A., 2010. Characteristics of Cereal Grains and Crop Residues as Solid Biomass Fuel. Master of Engineering Science thesis submitted to University College Dublin, July 2010.

Kirkegaard, J., Christen, O., Krupinsky, J., Layzell, D., 2008. Break crop benefits in temperate wheat production. Field Crops Research 107, 185–195.

Kreuger, E., Prade, T., Escobar, F., Svensson, S.E., Englund, J.E., Bjornsson, L., 2011. Anaerobic digestion of industrial hemp-Effect of harvest time on methane yield per hectare. Biomass and Bioenergy 35, 893–900.

Kuesters, J., Lammel, J., 1999. Investigation of the energy efficiency of the production of winter wheat and sugar beet in Europe. European Journal of Agronomy 11, 35–43.

McGettigan, M., Duffy, P., Connolly, N., O' Brien, P., 2006. National inventory report 2006: greenhouse gas emissions reported to the United Nations framework on climate change. Environment Protection Agency, Wexford 2006.

Matthews, R.B., Grogan, P., 2001. Potential C-sequestration rates under short rotation coppiced willow and Miscanthus biomass crops. A modelling study. Aspects of Applied Biology 65, 303–312.

Meijer, W.J.M., Van der Werf, H.M.G., Mathijssen, E.W.J.M., van der Brink, P.W.M., 1995. Constraints to dry matter production in fibre hemp (*Cannabis sativa* L.). European Journal of Agronomy 4 (1), 109–117.

O'Donovan, T., 2011. Crops costs and returns 2011. www.teagasc.ie/publications/>:

O'Mahony, J., 2009. Crops costs and returns 2009. www.teagasc.ie/publications/>.

O' Mahony, J., 2010. Crops costs and returns 2010. www.teagasc.ie/publications/>.

Plunkett, M., 2010. Application of Sewage Sludges and Biosolids to Energy Crops. In: Caslin, B., Finnan, J. (Eds.), Energy Crops Manual. Teagasc, Oak Park, Carlow, Ireland,

pp. 27–31In: Caslin, B., Finnan, J. (Eds.), Energy Crops Manual. Teagasc, Oak Park, Carlow, Ireland, pp. 27–31.

Prade, T., Svensson, S.E., Andersson, A., Mattson, J.E., 2011. Biomass and energy yield of industrial hemp grown for biogas and solid fuel. Biomass and Bioenergy 35, 3040–3049.

Rice, B., 2008. Hemp as a feedstock for biomass-to-energy conversion. Journal of Industrial Hemp 13 (2), 145–156.

Riche , A., 2005. A Trial on the Suitability of Switchgrass and Reed Canary Grass as Biofuel Crops Under UK Conditions. Final Report ETSU B/CR/00655/00/00.

Rosenqvist, H., Aronsson, P., Hasselgren, K., Perttu, K., 1997. Economics of using municipal wastewater irrigation of willow coppice crops. Biomass and Bioenergy 12, 1–8.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), 2007. Cambridge University Press.

Struik, P.C., Amaducci, S., Bullard, M.J., Stutterheim, N.C., Venturi, G., Cromack, H.T.H., 2000. Agronomy of fibre hemp (*Cannabis sativa* L.) in Europe. Industrial Crops and Products 11, 107–118.

Styles, D., Jones, M., 2007. Energy crops in Ireland: quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. Biomass and Bioenergy 31, 759–772.

Van der Werf, H.M.G., Mathijjen, E.W.J.M., Haverkort, A.J., 1996. The potential of hemp for sustainable fibre production: a crop physiological appraisal. Annals of Applied Biology 129, 109–123.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Journal of American Society of Soil Science 66, 1930–1946.

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Energy balances for biogas and solid biofuel production from industrial hemp

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ABSTRACT

If energy crops are to replace fossil fuels as source for heat, power or vehicle fuel, their whole production chain must have higher energy output than input. Industrial hemp has high biomass and energy yields. The study evaluated and compared net energy yields (NEY) and energy output-to-input ratios ($R_{O/I}$) for production of heat, power and vehicle fuel from industrial hemp. Four scenarios for hemp biomass were compared; (I) combined heat and power (CHP) from spring-harvested baled hemp, (II) heat from spring-harvested briquetted hemp, and (III) CHP and (IV) vehicle fuel from autumn-harvested chopped and ensiled hemp processed to biogas in an anaerobic digestion process. The results were compared with those of other energy crops. Calculations were based on conditions in the agricultural area along the Swedish west and south coast. There was little difference in total energy input up to storage, but large differences in the individual steps involved. Further processing to final energy product differed greatly. Total energy ratio was best for combustion scenarios (I) and (II) ($R_{O/I}$ of 6.8 and 5.1, respectively). The biogas scenarios (III) and (IV) both had low $R_{O/I}$ (2.7 and 2.6, repectively). They suffer from higher energy inputs and lower conversion efficiencies but give high quality products, i.e. electricity and vehicle fuel. The main competitors for hemp are maize and sugar beets for biogas production and the perennial crops willow, reed canary grass and miscanthus for solid biofuel production. Hemp is an above-average energy crop with a large potential for yield improvements.

1. Introduction

Biomass from agricultural crops has been suggested as an alternative source of energy that has the potential to partly replace fossil fuels for heat, power and vehicle fuel production [1–3]. The replacement of fossil fuels is desirable for the mitigation of CO_2 emissions among other aims. However, for mitigation of CO_2 emissions, replacement of fossil fuels with biofuels based on the energy content is crucial. The fossil fuels used for producing the biofuels must also be accounted for. Recent studies have challenged the ability of biofuels to reduce CO_2 emissions, e.g. ethanol from sugarcane or maize [4] or biodiesel from rapeseed oil [5]. Some biofuels have been reported to increase overall CO_2 emissions, when the complete well-to-wheel production pathway is considered (e.g. [6]). Important parameters influencing the environmental sustainability of biofuels include inflicted land-use change, utilisation of by-products or origin of auxiliary energy [7]. Major concerns relate to the resource efficiency of agricultural biomass production (e.g. [6]).

Energy crops are often compared in terms of resource efficiency, e.g. arable land type, environmental impact, energy and economic efficiency of the gaseous, liquid or solid energy carriers produced [8]. For each well-to-wheel production pathway an energy balance can be calculated that accounts for the energy outputs minus the direct and indirect energy inputs in cultivation, harvest, transport and conversion [9]. Energy balances have been drawn up for most of the first

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generation energy crops, for example maize (e.g. [10]) and wheat (e.g. [11]) for ethanol production and rape seed oil for biodiesel production (e.g. [12]). However, energy balances are lacking for many other crops that are in the stage of commercial introduction as energy crops, e.g. industrial hemp, or for new applications of common crops, e.g. biogas from residual agricultural biomass.

Hemp (*Cannabis sativa* L.) can be used to produce different energy products such as heat (from briquettes or pellets [13,14]), electricity (from baled biomass [15]) or vehicle fuel (e.g. biogas from anaerobic digestion [16]) or ethanol from fermentation [17]). Hemp has potential energy yields that are as high as or higher than those of many other energy crops common in northern Europe, e.g. maize or sugar beet for biogas production and reed canary grass as solid biofuel [18]. As an annual herbaceous crop, hemp fits into existing crop rotations. Hemp requires little pesticide and has been shown to have the potential to decrease pesticide use even for the succeeding crop [19], as it is a very good weed competitor [20]. These characteristics of hemp potentially improve the energy balance, as production of pesticides requires large amounts of energy [21]. Energy conversion of hemp biomass to biogas or ethanol has been shown to have promising energy yields [16,17]. Energy utilisation of hemp biomass processed to solid biofuels in the form of briquettes has been established commercially, and is competitive in a niche market [22].

When comparing energy crops with each other based on their environmental performance (e.g. emissions from production and use of fertiliser, fossil fuel, etc.), it is important to also know the emissions avoided by replacing other sources of energy, i.e. fossil fuels. However, this requires an energy balance, including the energy inputs and outputs of the conversion investigated. Earlier studies regarding the use of hemp for energy purposes have concentrated on calculating the emissions from sole biomass production [23], from electricity production from hemp-derived biogas [24], from hemp diesel production [25] and from hemp pulp production [26]. To our knowledge, no other energy use of hemp biomass (e.g. for biogas, ethanol or solid biofuel production) has been investigated in reference to its energy balance.

The aim of the present study was to evaluate and compare the energy balances of four scenarios for the production of hemp biomass and further fuel processing. These scenarios were: (I) combined heat and power (CHP) from spring-harvested baled hemp, (II) heat from spring-harvested briquetted hemp, and (III) CHP and (IV) vehicle fuel from autumn-harvested chopped and ensiled hemp processed to biogas in an anaerobic digestion process. An additional aim was to compare hemp with other biomass sources used for the final energy products investigated.

2. Methodology

2.1. Description of base scenarios

The different utilisation pathways for hemp biomass can be grouped in terms of two different biomass harvest times: Hemp harvested as green plants in autumn if intended for biogas, or as dry plants harvested in spring if intended for solid biofuel production [18]. To compare these pathways, four different energy conversion base scenarios were investigated (Fig. 1).

Scenario I describes combined heat and power (CHP) production from combustion of spring-harvested baled hemp. In this scenario, hemp would act as a complement to straw fuel in a large-scale CHP plant, e.g. as is common in Denmark [27]. In CHP production, the combustion heat is used for production of both electricity (power) and heat, e.g. for residential and commercial district heating.

Scenario II describes the production of heat from combustion of spring-harvested, chopped and briquetted hemp. This scenario illustrates the utilisation currently available in parts of Sweden, i.e. combustion in small-scale boilers for heating of private homes [28].

Scenario III describes the production of CHP from biogas derived by anaerobic digestion of autumn-harvested chopped and ensiled hemp. This scenario outlines how biogas (mostly from maize digestion) is commonly used in Germany [29].

Scenario IV describes the production of vehicle fuel from biogas derived by anaerobic digestion of autumn-harvested chopped and ensiled hemp. This scenario depicts the situation of how biogas (of other origin than hemp) is increasingly being used in Sweden, Germany and other European countries as vehicle fuel [30].

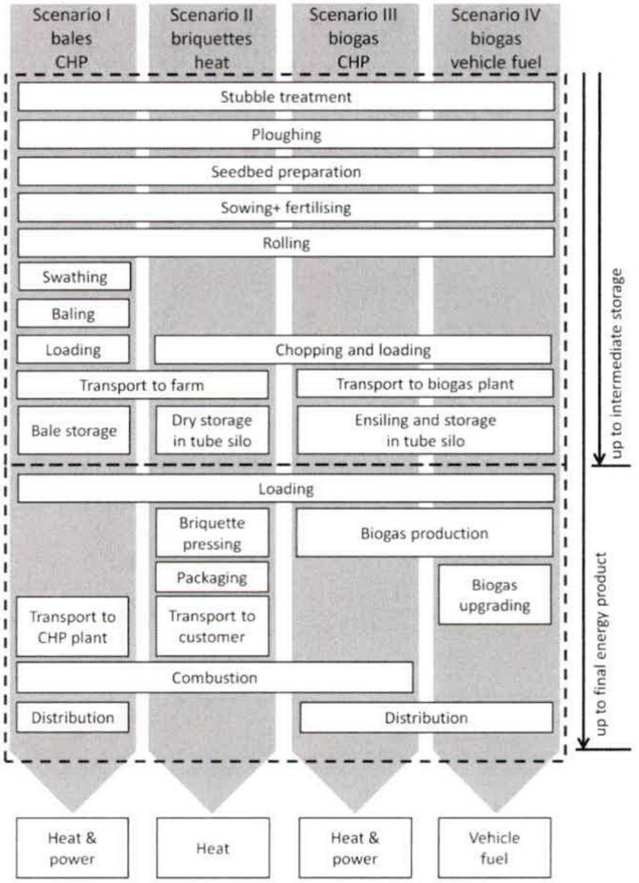

Fig. 1 – Schematic overview of the field and transport operations accounted for in CHP production from baled hemp (scenario I), heat production from briquetted hemp biomass (scenario II), CHP production from hemp-derived biogas (scenario III) and vehicle fuel production from hemp-derived biogas (scenario IV).

2.2. *Scenario assumptions*

2.2.1. *Cultivation area*

Hemp biomass was assumed to be produced in the agricultural area called *Götalands södra slättbygder*, Gss, extending over the Swedish west and south coast, up to 35 km inland (55°20′-57°06′ N, 12°14′-14°21′ E) [31]. On average, this area produces high yields per hectare of conventional crops. Gss comprises approx 330,000 ha arable land [31,32] and is also the area where hemp could be grown with relatively high biomass and energy yields per hectare [18]. A typical short crop rotation in this area is sugar beet followed by spring barley and winter wheat. This rotation was assumed to be extended with one year of hemp cultivation following either sugar beet or winter wheat. It was further assumed that the farm cultivates 150 ha arable land conventionally, with an average field size of 4 ha, reflecting the actual average farming situation in the agricultural area investigated [33].

2.2.2. *Soil treatment*

Soil treatment was assumed to comprise stubble treatment, ploughing and seedbed preparation. Sowing was assumed to be carried out in combination with fertilisation, with subsequent light soil compaction by a roller. Pesticide treatment was assumed to be unnecessary [19]. These field operations for establishing the hemp crop were identical for all scenarios tested in the present study.

2.2.3. *Scenario I*

Solid biofuel production in scenarios I and II requires harvest in spring, when moisture content (MC) in the biomass is below a mass fraction of 30% [18], which is required for safe, low-loss storage [34]. In scenario I, hemp was assumed to be cut and laid in swaths, then pressed into large square bales (2.4 m × 1.2 m × 1.3 m). The bales were transported 4 km on average to the farm (see section 2.4). For intermediate storage the bales were wrapped together in a plastic film tube, which is an economic storage option that does not require as much investment as permanent storage buildings. The bales were then transported on demand to a CHP plant, where they were combusted. A CHP plant with an annual production of 780 TJ (el) and 1430 TJ (th) was assumed, which is similar to the dimensions of existing large-scale straw-firing CHP plants, e.g. [27,35]. Baled wheat straw is typically the predominant fuel in such plants and was assumed to account for 95% of the energy produced in the present scenario. The remaining 5% were assumed to be accounted for by baled hemp biomass. The bales were fed into the boiler by means of a conveyor belt. The CHP plant was assumed to be equipped with a flue gas condensing unit for heat recovery [35]. Table 1 lists the major process parameters. The straw/hemp ash mixture was assumed to be transported back to the field and used for fertilising the soil for the next crop at 172 kg ha^{-1}. This dosage was derived from the total amount of ash produced during one year divided by the total annual cultivation area for hemp and straw combined [36]. A standard lime spreader was assumed for spreading of the ash.

2.2.4. *Scenario II*

For briquette production, hemp is also spring-harvested. Here it was assumed that hemp was chopped (20 mm length) with a maize forage harvester in the field and transported in bulk to the farm, where it was stored dry by compressing it into a silage tube for intermediate storage. Further processing included on-site pressing into briquettes, packaging and transport to local sales places and customers. It was further assumed that 50% of the briquettes were sold as 12 kg bags at petrol stations [40]. Individual transport of the briquettes to

Table 1 – Assumed and calculated process parameters used for modelling the CHP plant.

Parameter		Unit	Assumed value		Source
Nominal effect		MW (el)	35		[35]
		MW (th)	68		[35]
Electric efficiency		%	33		[35]
Thermal efficiency		%	60		[35]
Annual production		TJ	2384		Own calculations
			hemp	straw	
HHV		MJ kg^{-1}	19.1	18.7	[18,37]
Ash content		wt-%	1.8	5.0	[18,37]
Required DM biomass		Mg a^{-1}	6241	121,125	Own calculations
Required cultivation area		ha a^{-1}	1068	34,844	Own calculations
Nutrient removal[a]	N		24	29	
	P	kg ha^{-1}	10	4	Own unpublished results, [38]
	K		7	41	
Electricity production		TJ a^{-1}	787		Own calculations
Heat production		TJ a^{-1}	1431		Own calculations
Indirect energy input		% of produced electricity	4.0		[39]
Ash production		Mg a^{-1}	6165		Own calculations
Nutrient recycling[b]	P	%	38		Own calculations
	K	%	100		Own calculations

a Based on normalised yields for hemp and maize.
b Calculated from the content of P and K in the ash derived from the hemp/cereal straw fuel mix.

the place of combustion was not accounted for, as it was assumed that the bags were picked up 'on route'. The remaining 50% were assumed to be delivered to the place of utilisation in 450 kg bulk bags [40]. The average transportation distance for both bag sizes was calculated (see section 2.4) to be 30 km on average. In both cases, briquettes were assumed to be burned in small-scale domestic boilers (80% thermal efficiency) for heating purposes.

2.2.5. *Scenario III*

For the production of biogas, hemp is harvested in autumn when the biomass DM yield is highest [18]. In this scenario, it was assumed that the crop was harvested by chopping (20 mm length) with a maize forage harvester in the field and transported to the biogas plant, where it was ensiled in a silage tube for intermediate storage. The silage was then fed on demand to the biogas plant. In the biogas reactor the hemp was converted to biogas and a nutrient-rich digestate. The hemp biomass was assumed to be co-digested with maize in a medium-sized biogas plant with an annual production of 90 TJ raw biogas. This capacity corresponds to typical centralised or industrial biogas plants commonly digesting biomass from varying sources [41]. In the present scenario, hemp accounted for 20% of the energy produced, with maize accounting for the remainder. With such a low proportion of hemp, process parameters are likely to resemble those for a process run exclusively on maize. Therefore, this setup was assumed to be realistic for the implementation of a new energy crop as substrate in anaerobic digestion.

The raw biogas was assumed to be combusted in an on-site CHP plant (Fig. 2, top) with total annual production of 30 TJ (el) 40 TJ (th). Table 2 lists the major process parameters used in the present study. Pumping and mixing of the digestion process were assumed to use electricity from the grid, while heating of the biogas plant was assumed to use heat from the CHP process, internally using raw biogas as fuel [48].

The digestate was assumed to be stored at the biogas plant until utilisation as biofertiliser. Fertilisation with digestate was assumed to partly replace mineral fertiliser according to its nutrient content in the production of hemp biomass in the following growing season. Only plant-available ammonium nitrogen (NH_4–N) content in the digestate was assumed to replace mineral nitrogen fertiliser. The amount of NH_4–N in the digestate was calculated from biomass elemental analysis (unpublished results) assuming the degree of mineralisation of the biomass in the digestion process as the production rates of methane and carbon dioxide suggest. A mass fraction of 5% of NH_4–N were assumed lost in the handling and spreading of digestate [49]. Additional organically-bound N was not accounted for. All phosphorus (P) and potassium (K) removed from the fields with the harvested biomass was assumed to be returned through use of the digestate as biofertiliser and to directly replace mineral P and K fertiliser, respectively. Transport of digestate from biogas plant to field was assumed to be achieved by tank truck with no prior dewatering, as transport distances are relatively short [48].

2.2.6. *Scenario IV*

In scenario IV, hemp biomass was assumed to be used and treated as described in scenario III until the production of raw biogas. However, instead of combusting the biogas, it was refined to vehicle fuel (Fig. 2, centre). This upgrading was assumed to be carried out in a subsequent water scrubber unit, which is a common choice of technology in Sweden [45]. The upgrading unit increases the methane content to a volume fraction of 97% in the biogas, which is then pressurised to 20 MPa. The upgrading unit was assumed to have an annual nominal production of 90 TJ of biogas vehicle fuel. The biogas vehicle fuel was assumed to be distributed non-publicly directly at the biogas plant, e.g. for vehicles in public transport.

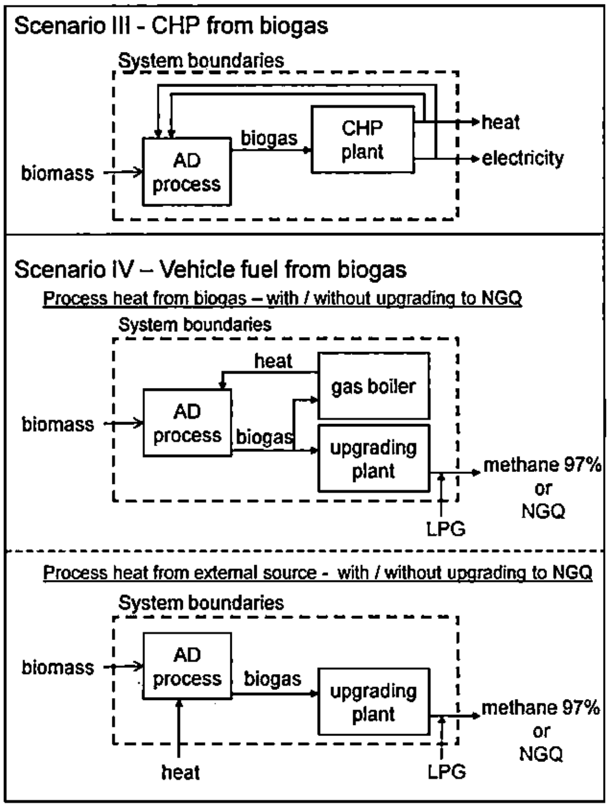

Fig. 2 – Schematic overview of the anaerobic digestion (AD) process and the subsequent utilisation of biogas for base scenario III (top). The centre panel depicts the pathway without (base scenario IV) and with an additional upgrading option from 97% methane content to natural gas quality (NGQ) vehicle fuel (subscenario, grey items). The bottom panel depicts the subscenarios using external heat for the AD process with and without the same upgrading option (grey items).

In contrast to scenario III, heating of the biogas plant was assumed to use heat from a gas boiler, using raw biogas as fuel [48]. Note that scenarios III and IV refer to the same amount of biomass utilised.

2.3. *Calculation of energy balances*

For all scenarios, the net energy yield (NEY) was calculated by subtracting the sum of direct and indirect energy inputs ($EI_{dir/ind}$) from the energy output (EO).

Table 2 – Assumed and calculated process parameters used for modelling the anaerobic digestion plant. The tables list the major direct and indirect energy inputs.

Parameter		Unit	Assumed value		References
Digester, size[a]		m^3	2600		Own calculations
Storage tank for digestate, size[b]		m^3	14,500		Own calculations
Feed as VS		$kg\ m^{-3}\ d^{-1}$	3.0		[42]
			hemp	maize	
Required DM biomass		$Mg\ a^{-1}$	2218	6377	Own calculations
Required cultivation area		$ha\ a^{-1}$	215	531	Own calculations
Specific methane yield[c] on VS		$m^3\ kg^{-1}$	0.22	0.32	[16, 24, 43]
Volatile solids content (of DM)		%	93	95	[16, 43]
Nutrient removal[d]	N	$kg\ ha^{-1}$	83	154	Own unpublished results [18,38],
	P	$kg\ ha^{-1}$	35	31	
	K	$kg\ ha^{-1}$	121	216	
Nutrient recycling	N[e]	%	55		Own calculations
	P	%	92		
	K	%	100		
Life time digester and storage		a			[44]
Direct energy input			20		
Heating		$GJ\ ha^{-1}\ a^{-1}$	3.6		[45]
Pumping & mixing		$GJ\ ha^{-1}\ a^{-1}$	0.8		[46]
Indirect energy input[f]					
Anaerobic digester		$GJ\ ha^{-1}\ a^{-1}$	0.49		
Digestate storage		$GJ\ ha^{-1}\ a^{-1}$	0.25		Own calculations
CHP plant (scenario III)		$GJ\ ha^{-1}\ a^{-1}$	0.52		

DM = dry matter; VS = volatile solids.

[a] Two units of 1300 m^3 each.

[b] Five units of 2900 m^3 each, dimensioned for the storage capacity for digestate accumulated over 8 months [47].

[c] Under standard gas conditions of 100 kPa and 273 K.

[d] Based on a normalised yield for hemp and maize.

[e] Calculated from 15% losses during digestion and spreading and a share of NH_4–N of 74% according to the degree of mineralisation during the digestion process.

[f] Indirect energy inputs from transport and assembly of building materials were assumed to be minor and were not accounted for. For simplicity, building materials included only steel, concrete and plastics, assuming a steel digestion reactor and a steel-reinforced concrete tank with plastic gastight roofing for storage of digestate.

$$NEY = EO - \left(\sum(EI_{dir}) + \sum(EI_{dir})\right)$$

The energy output represents the energy derived as electricity, useful heat and vehicle fuel from the conversion processes. The energy output-to-input ratio ($R_{O/I}$) was calculated by dividing the gross energy output by the accumulated energy input of each scenario.

$$R_{O/I} = EO/\left(\sum(EI_{dir}) + \sum(EI_{ind})\right)$$

These calculations were carried out for two different system boundaries: (a) From cultivation until intermediate storage of the hemp biomass (Fig. 1, top) and (b) from cultivation until distribution of the final energy product (Fig. 1, bottom).

The conversion efficiency (η_{conv}) was calculated for each scenario putting the energy output as final energy carrier in relation to the energy content in the harvested biomass:

$$\eta_{conv} = EO/E_{biomass}$$

2.3.1. *Energy input*

Table 3 lists the energy equivalents for production means that were assumed for energy input calculations. Energy input was calculated as the sum of direct and indirect energy inputs [52,62,63]. Direct inputs accounting for fuel consumption from field, transport and storage operations were assumed to be based on the use of fossil diesel, reflecting the current situation. Values for diesel consumption were taken from reference data [64]. Other direct energy inputs were heat energy (e.g. for heating the biogas digester) and electricity (e.g. for operation of the briquette press, digester pumping and mixing). Human labour and production and utilisation of non-storage buildings and dismantling/recycling of machinery and building materials were not accounted for, as these were regarded as minor. Solar radiation was not accounted for as it is free.

Indirect energy inputs accounted for the energy use in production of seeds, fertiliser, machinery, diesel fuel and electricity, as well as in maintenance (lubricants, spare parts) of the machinery used [65]. All fertiliser inputs other than digestate and ash were based on use of mineral fertilisers, according to common practice in conventional agricultural production. The energy contained in machinery was calculated based on the energy used for production of the raw material, the production process and maintenance and spare parts [66]. Machinery for soil treatment and briquette pressing is usually owned by the farmer and was assumed to be so in this study. Machinery capacity data ([64]; hemp harvest: unpublished results) was used to calculate the annual machinery-specific operating hours based on the assumed crop rotation (Table 4). Machinery and equipment for harvest

Table 3 – Primary energy factors and energy equivalents for the production means.

Item	Unit	Energy equivalent		References
		Value used	Literature low - high	
Diesel fuel energy content	MJ L^{-1}	37.4	35.9–38.7	[48,52,53,55,56]
Indirect energy use	MJ MJ^{-1}	0.19[a]	0.10–0.27	[50–52,55,56,58]
Electricity indirect energy use	MJ MJ^{-1}	1.20	1.12–1.92	[39,45,49,54]
Natural gas[b] energy content	MJ m^{-3}	39.6		[45]
Indirect energy use	MJ MJ^{-1}	1.2		[45]
LPG energy content	MJ m^{-3}	93		[61]
Indirect energy use	MJ MJ^{-1}	1.1		[45]
Mineral fertiliser N	MJ kg^{-1}	45.0[c]	37.5–70.0	[11,48,52,56,57,59,60]
P	MJ kg^{-1}	25.0[c]	7.9–39.9	[11,48,52,56,57,59,60]
K	MJ kg^{-1}	5.0[c]	4.8–12.6	[11,48,52,56,57,59,60]
Seeds	MJ kg^{-1}	10.1[d]	2.5–12.2	[55–57,59,60]

a 0.04 MJ MJ^{-1} for lubricants and 0.15 MJ MJ^{-1} for the manufacturing process.

b Natural gas was assumed to be used as external production option of heat for the anaerobic digestion process. Conversion efficiency was assumed to be $\eta = 0.96$ (th) [45]. The indirect energy for the conversion process was assumed insignificant.

c These values reflect the current trend of increasing energy efficiency in nitrogen fertiliser production and increasing energy demand for phosphorus fertiliser production [8].

d Based on the assumption of 7.5 MJ kg^{-1} for the production of the seeds, 0.6 MJ kg^{-1} for coating [60] and 2.0 MJ kg^{-1} for the transport (France-Sweden, 1800 km at 1.1 kJ kg^{-1} km^{-1} [59]).

and transport were assumed to be owned by a contractor, resulting in high numbers of annual machinery operating hours (Table 4).

The indirect energy for the straw-fired CHP plant was accounted for as 4% of the power produced [39]. Indirect energy for the building materials used for the anaerobic digester system was assumed on the basis of a simplified construction including a steel tank digester and steel-reinforced concrete tanks with gastight plastic roofing for storage of the digested residues. Indirect energy for the upgrading plant and for the transport, assembly and dismantling of the biogas plant was assumed to be minor and was not accounted for.

2.3.2. *Hemp biomass yields and energy output*

Assumptions of realistic hemp biomass dry matter (DM) yields, MC and corresponding heating values at harvest dates suitable for biogas and for solid biofuel production have been reported earlier [18] and were used unaltered in this study (Table 5). Harvest time-related biomass energy content was calculated from the biomass DM yields and the corresponding higher heating value (HHV) [18].

Table 5 lists the assumed values of parameters used in calculation of the energy balance. N fertilisation was assumed to follow recommendations for hemp cultivation [14,19]. P and K fertilisation was based on actual nutrient removal rates at the corresponding harvest time as derived from elemental analysis of biomass samples (unpublished results).

In modelling biogas production from hemp, harvest in September–October was assumed to result in a biomass DM yield of 10.2 Mg ha^{-1} [18] and a volatile solids (VS) content of 95% of the DM content [16]. The gross energy output as biogas was then calculated using a specific methane yield of 0.22 m^3 kg^{-1} of VS under standard gas conditions of 273 K and 100 kPa, which was assumed to be a realistic value in commercial production [16,24] (Table 5).

The energy output for the use of hemp biomass as solid biofuel was calculated from the hemp DM yield and the corresponding heating value: For combustion of bales in a CHP plant equipped with a heat recovery unit, the HHV was used. For combustion of briquettes in a simple boiler or wood stove, the lower heating value (LHV) was used. The biomass was assumed to be harvested in spring, corresponding to an MC of 15% and a DM yield of 5.8 Mg ha^{-1} [18]. The low MC is advantageous for combustion, but is also a requirement (MC $\leq$ 15%) for briquetting of the biomass [22].

2.4. *Transport distances*

Transport distances of biomass from field to storage and of digestate from biogas plant to field were calculated according to Eq. (1) [69]:

$$d = 2/3^{*}\tau^{*}r \quad (1)$$

where d (km) is the average transport distance, τ the tortuosity factor and r (km) the radius of the area (for simplicity assumed to be circular with the farm or processing plant in the centre) in which the transport takes place. The tortuosity factor describes the ratio of actual distance travelled to line of sight distance [69]. The parameter τ can range from a regular rectangular road grid ($\tau = 1.27$) to complex or hilly terrain constrained by e.g. lakes and swamps ($\tau = 3.00$) [69]. In this study a median value for τ of 2.14 was assumed.

Transport distances for briquettes to petrol stations and bulk customers were calculated as the radius for coverage of 25% of the study area, using Eq. (1). The coverage area was assumed to provide sufficient customers for the scope of briquette production studied.

2.5. *Distribution of energy products*

The final energy products have to be transported to the final consumers. In the case of heat this is accomplished in a local district heating grid connected to the heat-producing plant. Heat losses were assumed to be 8.2% [70]. Heat from briquette combustion was assumed to occur at the place of heat

Table 4 – Machinery specifications as used in the present study.

Operation	Machine type	Working width (m)	Weight (kg)	Power/power requirement[a] (kW)	Diesel consumption (L ha^{-1})	Annual use (h a^{-1})	Scenario use[b] (h ha^{-1})	Lifetime (a)	Indirect energy[c] (GJ)
Cultivation (all scenarios)									
Stubble treatment	Carrier	3.5	1700	88	8.6	200	0.5	10	67
Ploughing	4 furrow plough	1.4	1280	88	22.9	180	1.8	10	51
Seedbed preparation	Harrow combination	6.0	2500	77	5.7	90	0.4	12	99
Sowing/fertilisation	Seeding combination	3.0	2700	88	9.4	125	1.0	10	98
Rolling	Cambridge roller	6.0	4000	66	3.6	80	0.5	12	158
Spring harvest (as bales), scenario I									
Cutting & swathing	Windrower	4.5	5560	97	10.4	200	1.5	10	240
Baling	Square baler	3.0	9830	112	6.8	225	0.5	10	333
Loading and transport to farm	Wagon train	n.a.	5500	102	3.7	200	0.9	10	197
Storage in plastic wrapping	Bale wrapper	n.a.	4536	14	3.6	250	0.4	10	200
Loading of bales	Tractor with fork	n.a.	7000	100	0.5	850	0.9	12	309
Transport to CHP plant	Truck with trailer	n.a.	15,800	243	20.6	10^{6d}	41.0[e]	10	683
Unloading of bales	Tractor with fork	n.a.	7000	100	0.5	850	0.9	12	309
Loading of ash	Front loader	n.a.	13,500	105	0.03	1000	0,01	10	520
Transport of ash	Truck with container	n.a.	17,800	243	0.3	10^{6d}	0.5[e]	10	769
Spreading of ash	Tractor with spreader	n.a.	6400	60	0.7	110	0.2	10	278
Spring harvest (as bulk material) (scenario II)									
Cutting and chopping	Forage harvester	4.5	13,240	458	15.2	400	0.5	10	510
Collecting and transport to farm	Forage wagon	n.a.	6500	88	2.5	150	1.1	10	233
Storage	Tractor -driven tube press	n.a.	7000	147	15.9	210	0.2	12	261
Unloading/press feed	Front loader	n.a.	13,500	105	2.5	350	1.1	10	520
Briquette production	Briquette press	n.a.	2800	11	15[f]	1349	36	10	124
Transport to sales place	Truck with trailer	n.a.	15,800	243	5.8	10^{6d}	11.5[e]	10	683
Autumn harvest (as bulk material) (scenarios III and IV)									
Cutting and chopping	Forage harvester	4.5	13,240	458	21.1	400	0.7	10	510
Collecting and transport to biogas plant	Truck with dumper trailer	n.a.	15,246	295	29.0	10^{6d}	58.1[e]	10	659
Unloading/tube press feed	Front loader	n.a.	13,500	105	4.1	1684	1.1	10	520
Storage	Tractor -driven tube ensiling	n.a.	7000	147	17.7	160	0.6	12	261
Unloading/biogas plant feed	Front loader	n.a.	13,500	105	4.1	1684	1.1	10	520
Transport of digestate to field	Truck with tank trailer	n.a.	12,520	295	15.5	10^{6d}	30.9[e]	10	541
Spreading of digestate	Tractor with drag hose trailer	12	4300	200	8.6	358	0.5	10	186
Traction engines (all scenarios)									
For soil treatment operations	Tractor	n.a.	6000	88	n.a.[g]	650	n.a.[h]	12	230
For harvest, transport and storage operations	Tractor	n.a.	9500	200	n.a.[g]	850	n.a.[h]	12	364

n.a. = not applicable.

a Powering soil treatment operations assumed use of a 88 kW tractor. Powering of harvest, transport and storage operations assumed use of a 200 kW tractor.

b For hemp biomass production.

c Total lifetime indirect energy including, material, manufacture and maintenance. Calculated after [66,67] with energy coefficients for steel (17.5 MJ kg^{-1}), cast iron (10.0 MJ kg^{1}) and tyres (85 MJ kg^{-1}). Repair multipliers are taken from [66].

d Unit: km.

e Unit: km ha^{-1}.

f Unit: kWh.

g Included in the respective field operation.

h See respective field operation.

Table 5 – Assumed values for parameters used for calculation of the energy balance of hemp biomass production and utilisation as biogas substrate or solid biofuel, respectively. See section 2.2 for description of scenarios. Roman numerals indicate corresponding scenarios.

Parameter	Unit	Application of biomass as		References
		Solid biofuel	Biogas substrate[a]	
Scenarios		I and II	III and IV	
Cultivation				
N fertilisation[b]	kg ha^{-1}	150	150 (81)	[14, 19]
P fertilisation[c]	kg ha^{-1}	10	35 (32)	Unpublished results
K fertilisation[c]	kg ha^{-1}	8	123 (188)	Unpublished results
Seeds	kg ha^{-1}	20	20	[18]
Biomass				
Harvest period		February to April	September to October	[18]
Harvest losses	%	25	10	[18]
DM yield (after harvest losses)	Mg ha^{-1}	5.8	10.2	[18]
Moisture content	%	15	65	[18]
Specific methane yield[d] on VS	m^3 kg^{-1}	n.a.	0.22	[16,24]
Volatile solids content (of DM)	%	n.a.	93	[16]
HHV[e]	MJ kg^{-1}	19.1	18.4	[18]
LHV[f], dry basis	MJ kg^{-1}	17.4	12.6	[18]
Model				
Average field size	ha	4	4	[68]
Average transport distance				
field → farm storage (bales, bulk)	km	4	n.a.	[64]
farm storage → CHP plant (bales), CHP plant → farm (ash)	km	40 (I)	n.a.	Own calculations, section 2.4
farm storage → petrol station/bulk costumer (briquettes)	km	30 (II)	n.a.	Own calculations, section 2.4
field → biogas plant (bulk), biogas plant → field (digestate)	km	n.a.	15	Own calculations, section 2.4

n.a. = not applicable; DM = dry matter; VS = volatile solids.

a Number in brackets refers to the amount of N, P and K, respectively, derived from the recycling of digestate as biofertiliser. Note that recycling rates for potassium are higher than removal rates by hemp biomass, due to higher potassium removal rates by maize biomass, which accounts for 76% of the recycled digestate. Recycling was only accounted for up to 100% of the removal rates.

b The total nitrogen fertilisation level was assumed to be a fixed amount to ensure crop growth.

c Phosphorus and potassium fertilisation levels adjusted to the amount of nutrient removal.

d Under standard gas conditions of 100 kPa and 273 K.

e HHV = higher heating value.

f LHV = lower heating value.

utilisation, with distribution losses being negligible. Electricity was assumed to be distributed via the electrical grid with losses being 7.6% [70]. Biogas vehicle fuel was assumed to be distributed as 97% methane via a gas filling station directly at the biogas plant, where all biogas vehicle fuel was used for public transportation. As a subscenario to scenario III (section 2.6), biogas was assumed to be further upgraded to natural gas quality (NGQ) and transported to public petrol stations by a natural gas grid. The biogas pipeline to connect the biogas plant to the natural gas grid was assumed to be 25 km long, reflecting the geography of the study area and location of the natural gas grid (not shown).

2.6. *Sensitivity analysis*

A sensitivity analysis was carried out on subscenarios in order to investigate the effect of a number of parameters on the energy input and the NEY of hemp used for energy in all base scenarios.

Diesel consumption for cultivation and transportation, biomass DM yield and transport distances had been identified earlier as sensitive parameters in similar scenarios [71]. Therefore, these parameters were varied in subscenarios to all four base scenarios and their effect on the NEY recorded.

In scenario IV, biogas was assumed to be used to heat the anaerobic digestion process. It may be of economic interest to use all the biogas for upgrading to vehicle fuel, e.g. in order to maximise high value output. Therefore, a subscenario with an alternative external heat source was tested (Fig. 2, centre and bottom). A natural gas boiler ($\eta_{\text{thermal}} = 0.96$) was assumed to be used for external heat production [45].

Furthermore, in scenario IV the biogas vehicle fuel, which is similar to compressed natural gas (CNG), was assumed to be distributed at a gas filling station directly at the biogas plant. In a subscenario, the biogas was instead assumed to be distributed to public petrol stations via a natural gas grid (Fig. 2, centre and bottom). In such cases, biogas vehicle fuel is mixed with natural gas, requiring prior adjustment of the Wobbe index of the biogas (97% methane content) to NGQ in north-western Europe. This is usually done by adding liquid petroleum gas (LPG) to 8% content by volume [61]. Note that adjustment of the Wobbe index is only required where the heating value of the natural gas in the grid exceeds the heating value of the injected biomethane, e.g. in Sweden and Denmark [72]. For distribution in the local gas grid, compression of the biogas to only 0.5 MPa is sufficient. However, the biogas has to be compressed to 20 MPa at the gas station for further distribution.

3. Results

3.1. *Energy input in hemp biomass production up to intermediate storage*

The energy input in cultivation, harvest, transport and intermediate storage was found to be 11.7 and 13.0 GJ ha^{-1} for baled and briquetted solid biofuel production from spring-harvested hemp, respectively, and 12.2 GJ ha^{-1} for autumn-harvested, ensiled hemp biomass for biogas production (Fig. 3, top). Although the scenarios showed similar energy inputs, there were large differences in where these inputs were required. Nutrient recycling via digestate (see section 3.4) credited cultivation of autumn-harvested hemp with the use of a reduced amount of mineral fertiliser, resulting in 3.1–3.6 GJ ha^{-1} less energy input than in cultivation of spring-harvested hemp (Fig. 3, top). However, this was counterbalanced by higher requirements for storage and transport in autumn-harvested hemp (Fig. 3, top). Detailed results on direct and indirect energy input in cultivation, transport and intermediate storage are provided in Table 6.

3.2. *Energy balance of hemp biomass up to final energy product*

The four base scenarios differed substantially in their relative amount of energy input in the form of diesel, electricity, fertiliser, machinery and other equipment, production materials and heat requirements (Fig. 3, bottom).

Subsequent processing of the stored biomass requires energy inputs for conversion and additional transport. Conversion energy requirements differed substantially between the scenarios: inputs were low for solid biofuel combustion in the form of briquetted biomass (0.8 GJ ha^{-1}) and for CHP production from bales (1.5 GJ ha^{-1}) (Fig. 3, bottom). CHP production from biogas was more energy-intense (2.8 GJ ha^{-1}). The most energy-demanding conversion was the production of vehicle fuel (14.1 GJ ha^{-1}), where the upgrading of the biogas to 97% methane content represented 45% of the total energy input. This is reflected in the high amount of electricity required for scrubbing and compression of the biogas (Fig. 3, bottom).

The NEY was highest for CHP production from bales and heat from briquettes (Fig. 4), with high overall conversion efficiencies (86 and 80%, respectively) and high output-to-input ratios ($R_{O/I}$ of 6.8 and 5.1, respectively). The NEY of biogas CHP and vehicle fuel production was substantially lower. Conversion efficiency was 38% for upgraded biogas (vehicle fuel) and 22% for biogas CHP. Scenarios III and IV had a $R_{O/I} = 2.7$ and 2.6, respectively.

For each tonne DM increase in biomass yield, NEY increased by 15.7, 13.1, 3.9 and 5.8 GJ ha^{-1} for scenarios I to IV, respectively (Fig. 5, top). Fig. 5 (bottom) shows the influence of hemp biomass DM yield on $R_{O/I}$ for each scenario. The two solid biofuel scenarios were strongly yield-dependent, while the two biogas scenarios were far less sensitive to changes in biomass DM yield.

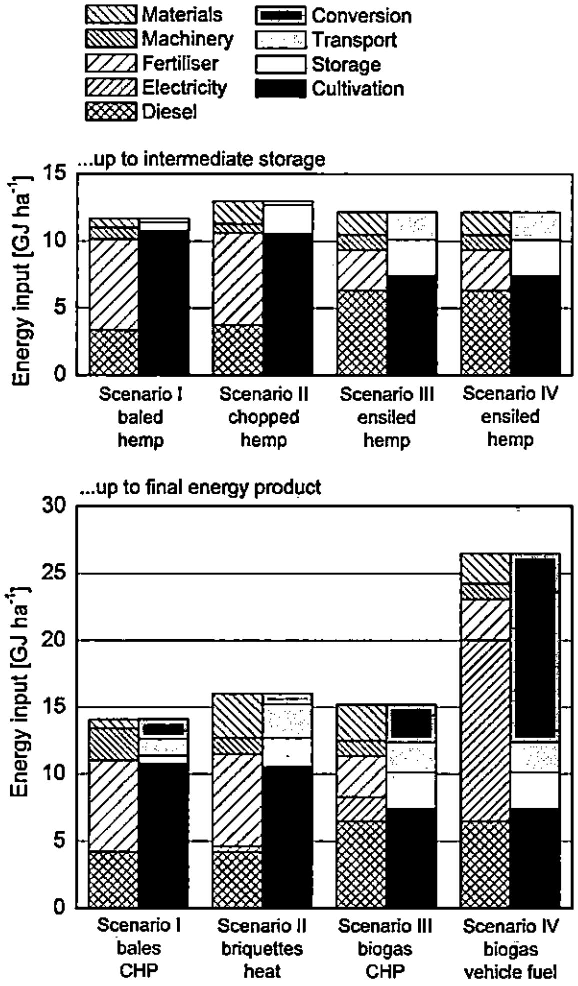

Fig. 3 – Energy inputs according to production means (left part of columns) and process stage (right part of columns) for scenarios I to IV. Energy inputs are given for hemp biomass production up to intermediate storage (top) and up to final energy product (bottom).

Consumption of indirect energy excluding fertiliser-related indirect energy, i.e. energy embodied in machinery and buildings and energy consumed in the production and distribution of the energy carrier used, such as diesel, accounted for 26, 35, 39 and 45% of the total energy input in scenarios I to IV, respectively. Fossil energy sources accounted for 95% of the total energy input for scenarios I to III and 86% for scenario IV.

3.3. *Variations in subscenarios*

Of the parameters tested, a ±30% change in biomass yield had a substantial effect on the absolute value for NEY in GJ ha^{-1}. This effect was largest for scenario III (±43%), followed by scenario IV (±38%) and scenarios I and II (±34 and ±35%, respectively) (Fig. 6). Changes in diesel consumption (±30%)

Table 6 – Direct and indirect energy input of fertilisation, field operations, transport and intermediate storage.

	Energy input – solid biofuel – *scenarios I and II*				Energy input – biogas – *scenarios III and IV*			
	Direct[a]		Indirect	Total	Direct[a]		Indirect	Total
Production means	(kg ha^{-1})		(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(kg ha^{-1})		(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})
Mineral fertiliser N	150		6750	6750	67		3009	3009
P *(scenario I/II)*	9/6		64/104	64/104	3		29	29
K *(scenario I/II)*	7/0		0/30	0/30	0		0	0
Seeds	20		270	270	20		270	270
Field/transport operation	(L ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(L ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})	(MJ ha^{-1} a^{-1})
Stubble treatment	8.6	322	97	419	8.6	322	97	419
Ploughing	22.9	856	278	1134	22.9	856	278	1134
Seedbed preparation	5.7	213	96	309	5.7	213	96	309
Sowing/fertilising combination	9.4	352	177	528	9.4	352	177	528
Ash/digestate spreading incl. transport etc. *(scenario I/II)*	1.0/0	37/0	15/0	52/0	24.0	902	665	1567
Compaction	3.6	135	123	258	3.6	135	123	258
Bale storage line[b]– *(scenario I)*								
Swathing	10.1	377	244	621				
Baling	6.6	247	141	388				
Loading/transport/unloading field-farm	3.5	131	150	281				
Storage in plastic film	3.6	135	471[d]	606				
Bulk storage line[c]–*(scenarios II, left; III and IV, right)*								
Cutting and chopping	15.1	566	168	734	21.0	787	234	1022
Collecting and transport	2.4	90	211	301	28.8	1075	242	1317
Ensiling/storage in tube baler	15.7	588	1564[e]	2152	17.5	654	1636[f]	2290
Total – bale storage line *(scenario I)*	75.0	2803	8875	11,679				
Total – bulk storage line *(scenarios II, left; III and IV, right)*	83.5	3122	9867	12,989	141.5	5295	6856	12,151

a Data on diesel consumption calculated from [64]. Values in L ha^{-1} a^{-1} represent diesel consumption.
b Spring harvest operation: The biomass is cut and swathed using windrower. The biomass is then pressed with a square baler. The bales are loaded onto a trailer using a tractor with a forklift.
c Autumn and spring harvest operation: The biomass is cut and chopped using a conventional forage harvester. The chopped biomass is blown into a tractor–wagon combination.
d Includes 414 MJ ha^{-1} for plastic wrapping for storage.
e Includes 1432 MJ ha^{-1} for plastic tube for storage.
f Includes 1415 MJ ha^{-1} for plastic tube for ensiling/storage.

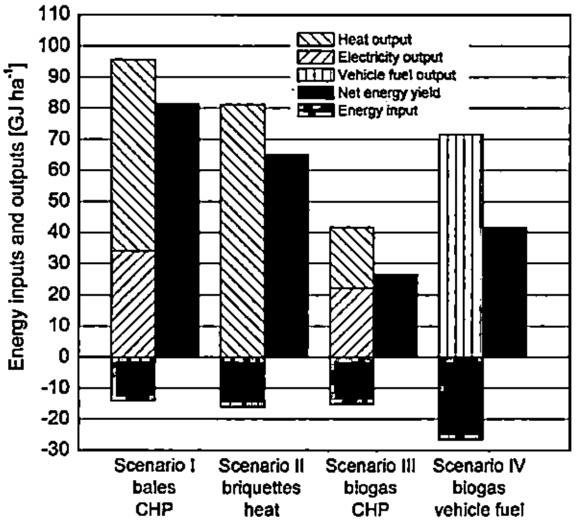

Fig. 4 – Energy output (white), energy inputs (grey) and net energy yields (black) for scenarios I to IV. Output energy shows heat, power and vehicle fuel production from hemp biomass.

and transport distance (−50%; +100%) influenced NEY by less than ±2% for solid biofuel production, by less than ±5% for vehicle fuel production from biogas and by less than ±8% for CHP production from biogas (Fig. 6).

The choice of heat source (internal biogas or external heating) as well as the choice of fuel quality and distribution form (upgrading to NGQ and distribution via natural gas grid) in scenario IV had only a marginal effect on NEY, which varied less by than 3% (Fig. 7).

3.4. *Nutrient recycling*

The large difference in energy input in biomass cultivation between autumn- and spring-harvested hemp is mainly due to replacement of mineral fertiliser by nutrient-rich digestate from the anaerobic digestion of autumn-harvested hemp. Based on the nutrient content of hemp and maize, 55, 92 and 100% of mineral N, P and K, respectively, could be replaced in the cultivation of autumn-harvested hemp (scenarios III and IV). This represents an energy saving of 4.6 GJ ha^{-1}, which corresponds to a reduction of 27% in the energy required for the cultivation and harvest of the biomass. The energy required for transport, storage and spreading of the digestate amounted to 1.6 GJ ha^{-1}.

Utilisation of ash from combustion of hemp (together with straw in scenario I) as a fertiliser had a much more limited impact on the energy balance than digestate. Based on the nutrient content of hemp and straw, 38 and 100% of mineral P and K fertilisers, respectively, could be replaced in the cultivation of spring-harvested hemp. All N is lost in the combustion process. The replacement of mineral fertiliser by utilising the nutrients in the ash corresponded to a saving of 0.07 GJ ha^{-1}. However, the energy required for transport and spreading of the ash amounted to 0.05 GJ ha^{-1}. Fertiliser energy input amounted to approx. 7 GJ ha^{-1} for scenarios I and II and 3 GJ ha^{-1} for scenarios III and IV. This corresponded to 48, 43, 20 and 11% of the total energy input in scenarios I to IV, respectively.

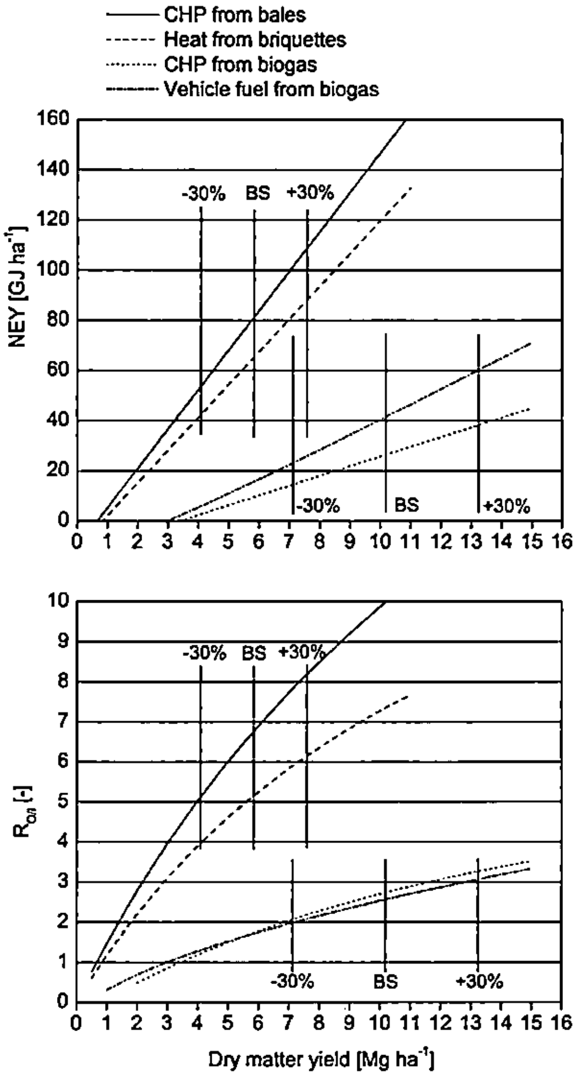

Fig. 5 – Energy output-to-input ratio ($R_{o/i}$) and net energy yield (NEY) as influenced by the biomass DM yield of hemp. Harvest losses of 25% for harvest as solid biofuel and 10% for harvest as biogas substrate [18] were subtracted from the biomass yield.

4. Discussion

4.1. *Comparison with other biomass sources*

A comparison of the net energy yield per hectare of hemp with that of other biomass sources based on published data is shown in Fig. 8. The biomass DM yield per hectare of hemp in the base scenario is rather conservative. Furthermore, hemp is a relatively new energy crop with great potential for yield improvements and yields 31% above the base scenario (3-year average) for both autumn and spring harvest have been

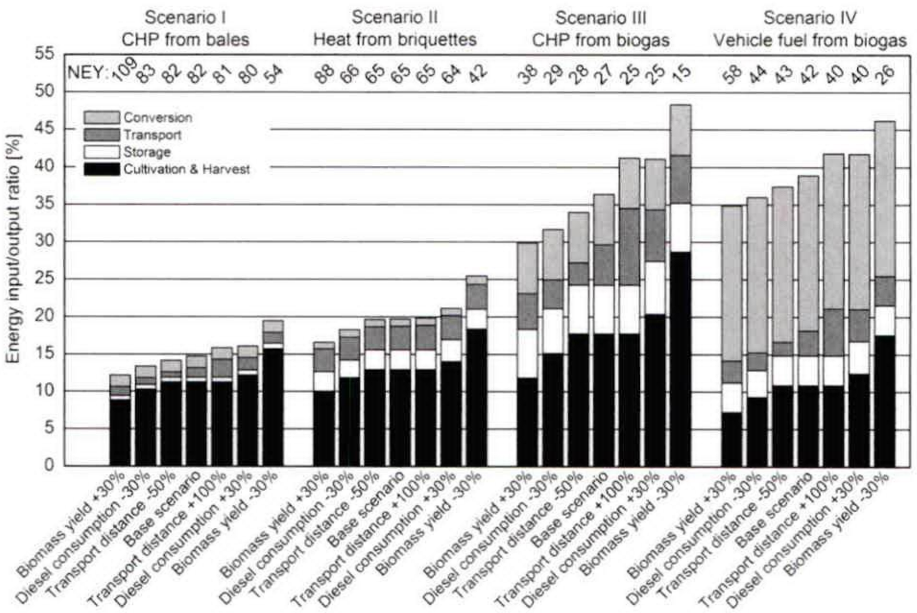

Fig. 6 – Sensitivity analysis for scenarios I to IV. Variation of the energy input/output ratio by changing biomass yield, transportation distance and diesel consumption. NEY = net energy yield, given in GJ ha^{-1}.

reported on good soils [18]. Therefore, in addition to the base scenario, the subscenario with biomass DM yield increased by 30% is shown (Fig. 8).

As harvested biomass in intermediate storage, hemp had similar NEY to other whole-crop silages, e.g. from maize and wheat and similar to sugar beet according to a comparison based on the energy content of the harvested biomass (Fig. 8, top). Sugar beet including tops had 24% higher NEY than hemp in the base scenario and a similar NEY to hemp with hemp biomass DM yields increased by 30%. Furthermore, since sugar beet requires about 70% higher energy input in biomass production, its energy $R_{O/I}$ is about 40% lower than that of hemp in the base scenario [8]. The NEY of ley crops seems rather low in comparison, but was based on 5-year average yields [8]. These are relatively low compared with those in highly intensive cultivation due to a high proportion of lower-yielding organic cultivation and to partly less intensive cultivation techniques [31].

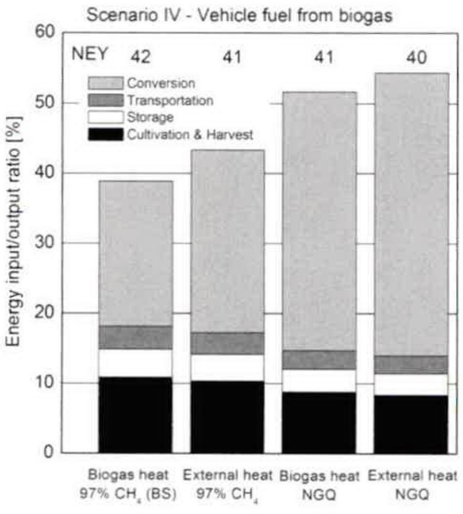

Fig. 7 – Sensitivity analysis for scenario IV. Variation of the energy input/output ratio by changing heat and electricity source and upgrading quality. BS = base scenario. NEY = net energy yield, given in GJ ha^{-1}.

For solid biofuel production, hemp biomass NEY was substantially lower than that of perennial energy crops such as miscanthus or willow, and even that of whole-crop rye (Fig. 8, top). Hemp has a similar biomass NEY to reed canary grass (Fig. 8, top), which is reflected in similar heat and CHP production of these two crops (Fig. 8, centre). Production of electricity only, i.e. not CHP, from hemp is relatively inefficient with $R_{O/I}$ only 2.6 (Fig. 8, centre). Even if the NEY of willow were recalculated for a comparable electric efficiency [74] and a comparable biomass DM yield (not shown) [75] as in the present study, it would still be about twice that of hemp (not shown).

Production of raw biogas from hemp has similar NEY to that of ley crops, while maize has about twice the NEY of hemp (Fig. 8, bottom), mostly due to higher specific methane yield [77]. These results are reflected again in electricity and vehicle fuel production from biogas (upgraded) for these crops. Miscanthus and willow grown in Denmark and southern Sweden have a higher biomass yield, while their methane potential is similar to that of hemp (not shown), resulting in 43 and 28% higher NEY, respectively (Fig. 8, bottom). With a 30% increase in biomass yield, hemp has a similar NEY to miscanthus and willow, while maize still has 50% higher NEY.

Generally for all biomass sources, electricity production from biogas has a relatively low NEY due to the double conversion biomass to biogas and biogas to electricity. The NEY could be improved if the heat from power generation were used for heating purposes, i.e. in residential or commercial heating by employing combined heat and power (CHP) production. With a 30% increase in biomass, hemp in

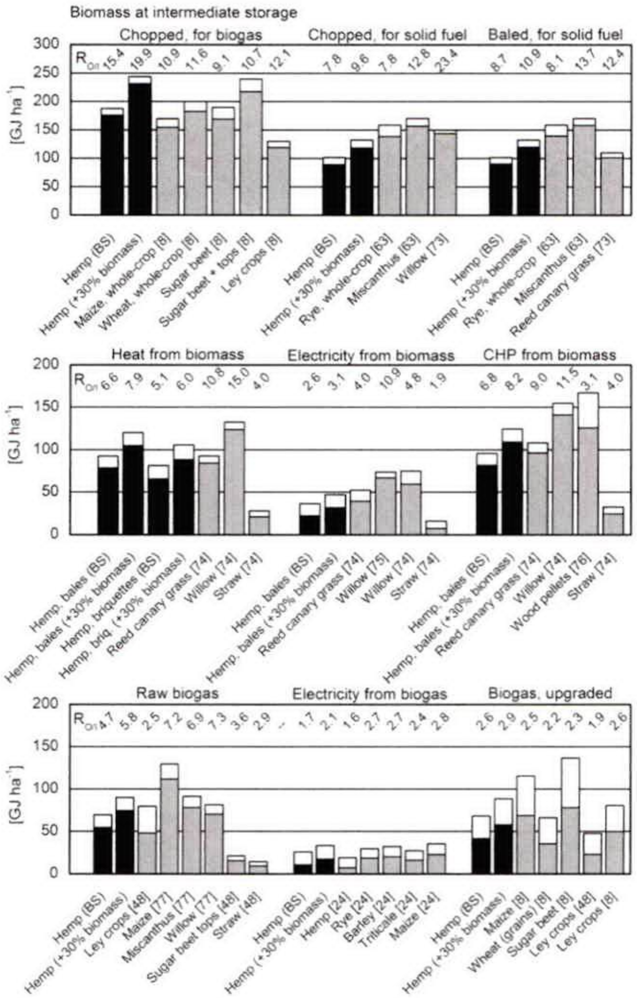

Fig. 8 – Net energy yield for biomass energy content at intermediate storage (top), heat, electricity and CHP from biomass (centre) and raw biogas, electricity from biogas and upgraded biogas (bottom). Black columns denote data for hemp from the present study, both the base scenario (BS) and the subscenario with biomass yields increased by 30%. Grey columns denote individual results from published data [8,24,48,63,73–77]. Numbers in brackets refer to the corresponding reference. The white part of the columns indicates the corresponding energy input. The corresponding output-to-input ratio ($R_{O/I}$) is shown above each column.

the present study had similar NEY to triticale and 7, 16 and 32% lower NEY than rye, barley and maize, respectively (Fig. 8, bottom). Another study has found a lower NEY for hemp, due to lower energy output [24].

For the production of upgraded biogas, sugar beet has a substantially higher NEY than hemp, mainly due to much higher methane potential. However, since energy inputs for utilisation of sugar beet are substantially higher than those of hemp, the $R_{O/I}$ is similar to that of hemp.

Comparison of the data from the present study to that from other studies also shows that the production and conversion models employed for calculating the energy balance can differ substantially, the two most variable parameters being the biomass DM yield (e.g. due to fertilisation, climate and soil conditions) and the conversion efficiency (e.g. due to methane potential, thermal/electrical efficiencies of the technology of choice). For example, it is often unclear whether dry matter yields are based on experimental data or data on commercial production, i.e. accounting for field and harvest losses. A comparison of this kind therefore needs to bear in mind the variability of assumptions upon which the investigated scenarios are based.

4.2. *Energy-efficient utilisation of hemp biomass*

Hemp biomass can be utilised in many different ways for energy purposes. However, the four scenarios investigated in the present study exhibited large differences in conversion efficiency, energy output and NEY. When directly comparing the outcome of the scenarios, it should be noted that energy products of different energy quality were compared. Higher quality energy products often require higher energy inputs and have more conversion steps where losses occur, as well as lower conversion efficiencies. For example, biogas vehicle fuel has a high energy density and can be stored with minimal losses. In contrast, heat can be generated with high conversion efficiency, but utilisation is restricted to short-term use in stationary installations (e.g. a district heating grid). However, the direct comparison of energy products derived from the same biomass source can show the best alternative utilisation pathway in a specific situation.

Just as for many other energy crops, utilisation of hemp has not yet been implemented on a large scale. This study shows examples of how relatively small cultivation areas of hemp can be utilised for production of renewable energy products, e.g. briquette production. However, large-scale hemp biomass utilisation can be implemented with the hemp acting as co-substrate for biogas production or co-fired solid biofuel.

The most efficient energy conversion is from hemp biomass to heat and power by combustion, e.g. of bales (scenario I). This is in agreement with a review of findings that puts the highest energy yields at 170–230 GJ ha^{-1} [78]. A 30% increase in the biomass DM yield of hemp would result in hemp being just above the upper limit, i.e. in a very competitive spot, together with most perennial crops.

Since heat has a low energy quality, this option is only viable where heat can be utilised in adequate amounts, e.g. in large-scale biomass CHP plants which are common in Denmark (straw-fired) and Sweden (wood fuel-fired) [27,35,79,80]. The highest energy quality is found in biogas vehicle fuel, which in this study has approx. 30% lower energy output per hectare than CHP from biomass. This option also had the highest energy input of all four scenarios. The option with the lowest conversion efficiency and the lowest energy output and NEY is CHP from biogas. This option only makes sense for wet biomass sources where combustion is not an option, e.g. manure or food wastes, but not for dedicated energy crops such as hemp or maize. Nonetheless, electricity from biogas has become more common in Germany, where feed-in tariffs render this option economically attractive, even though the combustion heat is often only used for electricity production, i.e. the heat energy in the exhaust gases is not used for heating purposes.

Ethanol production from hemp was not investigated in the present study, since this is an option with very high energy inputs [78]. Energy yields from combined ethanol production from hemp and biogas production from the stillage are only marginally higher than that of direct biogas production from the same biomass [81], indicating that an additional conversion process for ethanol production seems to be rather inefficient.

4.3. *Importance of nutrient recycling*

Replacement of mineral fertiliser by digestate corresponded to a saving of 4.4% of the energy content of the biogas produced, including the energy inputs for storage, transport and spreading of the digestate. This confirms earlier findings (2–8%) [48]. Ash recycling resulted in minor replacement of mineral fertiliser. In addition, ash utilisation as a fertiliser required a similar amount of energy, making this option less interesting from an energy balance point of view. However, in light of future phosphorus deposit depletion [82], recycling of ash is an important tool for closing nutrient cycles [83].

It has been shown that less than 100% of recycled nutrients are available to plants directly when spread on the field [78]. The present study did not address this issue, based on the assumption that fractions of nutrients (e.g. of P, K) not available to plants would replenish soil nutrient pools in the long-term. The content of micronutrients and organically-bound macronutrients (N, P, K) was also not accounted for in the present study, but potentially leads to a long-term fertilisation effect. These findings support the concept that nutrient recycling can be important for the overall energy sustainability of biofuels from agricultural energy crops [78].

The present study employed the concept of recycling the same amount of nutrients (minus losses) as were removed with the biomass from the same area of land. This was done irrespective of potential national and regional restrictions as may apply for the utilisation of digestate and ash in agriculture, based on e.g. content of nutrients and heavy metals [84]. Although a detailed discussion of this topic was outside the scope of this paper, its importance for maintaining a healthy basis for agriculture must be recognised.

4.4. *Potential future hemp energy yield improvements*

Use of hemp as an energy crop started only recently with the establishment of new cultivars with low THC content and the corresponding lifting of the ban on hemp cultivation that existed in many European countries until the early 1990s [19]. Therefore, hemp has been developed little as an industrial crop over the past decades [19]. In comparison to well-established (food) crops, hemp has great potential for improvement, e.g. increased biomass yields or conversion efficiencies. Improvements in harvesting technology could reduce harvesting losses, especially in spring harvesting of dry hemp [85].

The low energy conversion efficiency from hemp biomass to biogas may indicate that NEY can be increased by pretreatment of hemp biomass prior to anaerobic digestion, e.g. grinding or steam explosion [81]. Combined steam and enzyme pretreatment of biomass prior to anaerobic digestion could improve the methane potential of hemp by more than 25% [81]. Hydrolysis of maize and rye biomass with subsequent parallel biogas and combustion processes resulted in around 7–13% more energy output, although energy input requirements were 4–5 times higher than when biomass was only digested anaerobically [86]. Energy input for production of hemp biomass for both solid biofuel and biogas purposes is relatively low, situated together with maize at the lower end of the range for annual whole-crop plants [78]. Only perennial energy crops require less average annual energy input over the lifetime of the plantations [78].

4.5. *Environmental impact*

The change in energy source for heating the biogas process in the vehicle fuel option did not have a significant influence on NEY. However, the choice of external heat source may have significant environmental effects. There is probably also a profound economic effect, since heating fuels of lower energy quality (e.g. wood chips, straw or other agricultural residues) could be used for heating the biogas fermenter and about 5% more biogas could be upgraded to vehicle fuel. All scenarios examined here were characterised by high fossil energy input ratios. Fossil diesel accounted for more than 25% of the total energy input in all scenarios. In an environmental analysis, a change of fuel to renewable sources could potentially improve the carbon dioxide balance considerably.

Based on the energy balance for each scenario, the environmental influence of the energy utilisation of hemp can be evaluated, e.g. in a life cycle assessment (LCA). LCAs have been reported for the production of hemp biomass [23], biodiesel [25] and electricity from hemp-derived biogas [24]. However, LCAs for other options such as large-scale combustion for CHP, heat from hemp briquettes or vehicle fuel from hemp-derived biogas are lacking.

4.6. *Competitiveness of hemp*

Hemp can become an interesting crop where other energy crops cannot be cultivated economically (e.g. maize, sugar beet and miscanthus further north in Sweden and other Nordic countries) or where an annual crop is preferred (e.g. to perennial willow, miscanthus or reed canary grass). Due to its advantages in the crop rotation (good weed competition) and marginal pesticide requirements, hemp can also be an interesting crop in organic farming.

Hemp as an energy crop can compete with other energy crops in a number of applications. For solid biofuel production, perennial energy crops, such as willow, miscanthus and reed canary grass, are the main competitors of agricultural origin. Willow and miscanthus have a substantially higher NEY than hemp, but are grown in perennial cultivation systems, binding farmers to the crop over approx. 10–20 years. To achieve a similarly high NEY for hemp, above-average biomass DM yields are required and have been demonstrated on good soils [18].

For biogas production, maize and sugar beet are the main competitors. Maize and sugar beet have often a similar or slightly higher biomass yield than hemp, but a substantially higher methane potential [64,87]. However, energy inputs for utilisation of sugar beet as biogas substrate are high, resulting in similar $R_{O/I}$ to hemp. With increasing latitude of the cultivation site, the growing season becomes shorter and colder, which decreases the DM yield of maize (C_4-plant) faster than that of hemp (C_3-plant) [88]. This is reflected in commercial production in Sweden, where maize and sugar beet are grown up to latitudes of 60° N [1,88]. Hemp can be grown even further north with good biomass yields [89].

5. Conclusions

Hemp has high biomass DM and good net energy yields per hectare. Furthermore, hemp has good energy output-to-input ratios and is therefore an above-average energy crop. The combustion scenarios had the highest net energy yields and energy output-to-input ratios. The biogas scenarios suffer from higher energy inputs and lower conversion efficiencies but give higher quality products, i.e. electricity and vehicle fuel.

Hemp can be the best choice of crop under specific conditions and for certain applications. Advantages over other energy crops are also found outside the energy balance, e.g. low pesticide requirements, good weed competition and in crop rotations (annual cultivation). Future improvements of hemp biomass and energy yields may strengthen its competitive position against maize and sugar beet for biogas production and against perennial energy crops for solid biofuel production.

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REFERENCES

[1] Börjesson P. Bioenergi från jordbruket – en växande resurs. Stockholm, Sweden: Jordbruksdepartementet - Statens Offentliga Utredningar; 2007 May. 496 pp. Report No SOU 2007:36.

[2] EEA. Estimating the environmentally compatible bioenergy potential from agriculture. Copenhagen: European Environment Agency; 2008 Jan. 138 pp. Technical report No 12/2007.

[3] Hoogwijk M, Faaij A, Eickhout B, de Vries B, Turkenburg W. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. Biomass Bioenergy 2005;29:225–57.

[4] Scharlemann JPW, Laurance WF. How green are biofuels? Science 2008;319(5859):43–4.

[5] Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos Chem Phys 2008;8:389–95.

[6] Zah R, Böni H, Gauch M, Hischier R, Lehmann M, Wägner P. Ökobilanz von Energieprodukten - Ökologische Bewertung von Biotreibstoffen. St Gallen, Switzerland: Empa; 2007 May. 161 p. Publication No 270020.

[7] Börjesson P. Good or bad bioethanol from a greenhouse gas perspective – What determines this? Appl Energy 2009;86(5):589–94.

[8] Börjesson P, Tufvesson LM. Agricultural crop-based biofuels - resource efficiency and environmental performance including direct land use changes. J Cleaner Prod 2011;19(2-3):108–20.

[9] Moerschner J, Gerowitt B. 6. Direct and indirect energy use in arable farming-an example on winter wheat in Northern Germany. In: Weidema BP, Meeusen MJG, editors. Agricultural data for life cycle Assessments. The Hague, The Netherlands: Agricultural Economics Research Institute (LEI); 2000. p. 91–104.

[10] Pimentel D. Ethanol fuels: energy balance, economics, and environmental impacts are negative. Nat Resour Res 2003;12(2):127–34.

[11] Börjesson P. Energy analysis of biomass production and transportation. Biomass Bioenergy 1996;11(4):305–18.

[12] Janulis P. Reduction of energy consumption in biodiesel fuel life cycle. Renew Energy 2004;29(6):861–71.

[13] Bernesson S. Hampa till bränsle, fiber och olja. Köping, Sweden: Sveriges Energiföreningars Riksorganisation (SERO); 2006. 56 p.

[14] Sundberg M, Westlin H. Hampa som bränsleråvara. Uppsala, Sweden: JTI Institutet för jordbruks- och miljöteknik; 2005. 32 p. JTI Report Lantbruk & Industri 341.

[15] Mattsson JE. Affärsutveckling - Närodlade stråbränslen till kraftvärmeverk. Alnarp, Sweden: Swedish University of Agricultural Sciences (SLU); 2006. 98 pp. Rapport No 2006:8.

[16] Kreuger E, Prade T, Escobar F, Svensson S-E, Englund J-E, Björnsson L. Anaerobic digestion of industrial hemp–Effect of harvest time on methane energy yield per hectare. Biomass Bioenergy 2011;35(2):893–900.

[17] Sipos B, Kreuger E, Svensson S-E, Rézcey K, Björnsson L, Zacchi G. Steam pretreatment of dry and ensiled industrial hemp for ethanol production. Biomass Bioenergy 2010;34(12):1721–31.

[18] Prade T, Svensson S-E, Andersson A, Mattsson JE. Biomass and energy yield of industrial hemp grown for biogas and solid fuel. Biomass Bioenergy 2011;35(7):3040–9.

[19] Bocsa I, Karus M. The Cultivation of Hemp: botany, varieties, cultivation and harvesting. Sebastopol, USA: Hemptech; 1998.

[20] Lotz LAP, Groeneveld RMW, Habekotte B, Oene H. Reduction of growth and reproduction of Cyperus esculentus by specific crops. Weed Res 1991;31(3):153–60.

[21] Pimentel D. Energy inputs for the production, formulation, packaging, and transport of various pesticides. In: Pimentel D, editor. Handbook of energy utilization in agriculture. Boca Raton, USA: CRC Press; 1980. p. 45–8.

[22] Forsberg M, Sundberg M, Westlin H. Småskalig brikettering av hampa. Uppsala, Sweden: JTI Institutet för jordbruks- och miljöteknik; 2006. 34 p. JTI Report Lantbruk & industri 351.

[23] van der Werf HMG. Life cycle analysis of field production of fibre hemp, the effect of production practices on environmental impacts. Euphytica 2004;140(1):13–23.

[24] Plöchl M, Heiermann M, Linke B, Schelle H. Biogas crops – Part II: balance of greenhouse gas emissions and energy from using field crops for anaerobic digestion. Agric Eng Int CIGR 2009;XI:1–11.

[25] Casas XA, Rieradevall i Pons J. Environmental analysis of the energy use of hemp–analysis of the comparative life cycle: diesel oil vs. hemp–diesel. Int J Agric Res Gov Ecol 2005;4(2):133–9.

[26] González-García S, Hospido A, Moreira MT, Feijoo G. Life cycle environmental analysis of hemp production for

non-wood pulp. In: 3rd international conference on life cycle management; 2007. Zürich, Switzerland. p. 1–6.

[27] Hinge J. Elaboration of a Platform for increasing straw combustion in Sweden, based on Danish Experiences. Stockholm, Sweden: Värmeforsk; 2009. 80 p. Report No 1115.

[28] Bioenergiportalen. Hampa i Gudhem. [Internet]. Uppsala, Sweden: JTI. accessed [06.10.2011]. Available from: http://www.bioenergiportalen.se/?p=1561&pt=7; 2007.

[29] Schüsseler P. Bedeutung des Sektors Biogas im Rahmen der Erneuerbaren Energien. In: Institut für Landtechnik und Tierhaltung F-W, Germany. Internationale Wissenschaftstagung Biogas Science 2009. Erding, Germany: Bayerische Landesanstalt für Landwirtschaft; 2009. p. 9–20.

[30] Börjesson P, Mattiasson B. Biogas as a resource-efficient vehicle fuel. Trends Biotechnol 2008;26(1):7–13.

[31] SCB. Normskördar för skördeområden, län och riket 2009. Jönköping, Sweden: Statistics Sweden; 2009. 66 pp. Report No JO 15 SM 0901.

[32] SCB. Yearbook of agricultural statistics 2010. Jönköping, Sweden: Statistics Sweden; 2010. 390 p.

[33] SJV. Statistikdatabasen - Genomsnittlig areal (JEU), hektar per företag efter typgrupp/storleksklass. [Internet]. Jönköping, Sweden: Swedish Board of Agriculture. accessed [18.10.2010]. Available from: http://www.jordbruksverket.se/swedishboardofagriculture.4.6621c2fb1231eb917e680002462.html; 2008.

[34] Festenstein GN, Lacey J, Skinner FA, Jenkins PA, Pepys J, Lacey J. Self-heating of hay and grain in Dewar flasks and the development of farmer's lung antigens. J Gen Microbiol 1965; 41(3):389–407.

[35] Sander B, Skøtt T. Bioenergy for electricity and heat – experiences from biomass-fired CHP plants in Denmark. Fredericia, Denmark: DONG Energy; 2007. 76 p.

[36] Marmolin C, Ugander J, Gruvaeus I, Lundin G. Aska från halm och spannmål - kemisk sammansättning, fysikaliska egenskaper och spridningsteknik. Uppsala, Sweden: JTI - Swedish Institute of Agricultural and Environmental Engineering; 2008. JTI Report Lantbruk & industri 362.

[37] van Loo S, Koppejan J. The Handbook of biomass combustion and co-firing. Sterling, USA: Earthscan; 2008.

[38] Focus on Nutrients. Nutrient balance calculator. [Internet]. Jönköping, Sweden: Swedish Board of Agriculture. accessed [06.02.2011]. Available from: http://www.greppa.nu/vaxtnaringsbalans; 2011.

[39] Hartmann D, Kaltschmitt M. Electricity generation from solid biomass via co-combustion with coal - Energy and emission balances from a German case study. Biomass Bioenergy 1999; 16:397–406.

[40] Jonsson S. Hampabriketter. [Internet]. Falköping, Sweden: Gudhems Kungsgård. accessed [29.06.2011]. Available from: http://www.gudhemskungsgard.se/prod01.htm; 2011.

[41] SEA. Produktion och använding av biogas år 2008. Eskilstuna, Sweden: Swedish Energy Agency; 2010. Report No ES2010:01.

[42] Salter A, Banks CJ. Establishing an energy balance for crop-based digestion. Water Sci Technol 2009;59(6):1053–60.

[43] Schittenhelm S. Chemical composition and methane yield of maize hybrids with contrasting maturity. Eur J Agron 2008; 29(2-3):72–9.

[44] Hartmann JK. Life-cycle-assessment of industrial scale biogas plants. Göttingen, Germany: Faculty of Agricultural Sciences, University of Göttingen; 2006. 205 p.

[45] Lantz M, Ekman A, Börjesson P. Systemoptimerad production av fordonsgas. Lund, Sweden: Department of Technology and Society, Lund University; 2009. 110 p. Report No 69.

[46] Pabón Pereira CP. Anaerobic digestion in sustainable biomass chains. Wacheningen, The Netherlands: Centre for Sustainable Development and Food Security, University of Wacheningen; 2009. 262 p.

[47] Loch V. Sechs Monate sind zu wenig. dlz Agrarmagazin. Munich, Germany; 2007. pp. 56–58.

[48] Berglund M, Börjesson P. Assessment of energy performance in the life-cycle of biogas production. Biomass Bioenergy 2006;30(3):254–66.

[49] Börjesson P, Berglund M. Miljöanalys av biogassystem. Lund, Sweden: Department of Technology and Society, Lund University; 2003. 79 p. Report No 45.

[50] Bernesson S, Nilsson D, Hansson P-A. A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions. Biomass Bioenergy 2004;26:545–59.

[51] Börjesson P. Energianalys av drivmedel från spannmål och vall. Lund, Sweden: Department of Technology and Society. Lund University; 2004. 26 p. Report No 54.

[52] Dalgaard T, Halberg N, Porter JR. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. Agric Ecosyst Environ 2001;87: 51–65.

[53] Davis J, Haglund C. Life cycle inventory (LCI) of fertiliser production - Fertiliser products used in Sweden and Western Europe. Gothenburg, Sweden: Chalmers University of Technology; 1999. 112 p.

[54] EC. Proposal for a directive of the European parliament and of the council on the promotion of the use of energy from renewable sources. Commission of the European Communities; 2008.

[55] Kelm M, Wachendorf M, Trott H, Volkers K, Taube F. Performance and environmental effects of forage production on sandy soils. III. Energy efficiency in forage production from grassland and maize for silage. Grass Forage Sci 2004; 59:69–79.

[56] Reinhardt GA. Energie- und CO_2-Bilanzierung nachwachsender Rohstoffe. Brauschweig/Wiesbaden, Germany: Vieweg; 1993.

[57] Rosenberger A, Kaul HP, Senn T, Aufhammer W. Improving the energy balance of bioethanol production from winter cereals: the effect of crop production intensity. Appl Energy 2001;68(1):51–67.

[58] Scharmer K, Gosse G. Ecological impact of biodiesel production and use in europe. In: Moore A, editor. Proceedings of the 2nd European Motor biofuels Forum; 1996. Graz, Austria. p. 8–12.

[59] Smyth BM, Murphy JD, O'Brien CM. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? Renew Sustain Energy Rev 2009;13(9):2349–60.

[60] Wells C. Total energy Indicators of agricultural sustainability: Dairy farming case study. Otago, New Zealand: Department of Physics, University of Otago; 2001. 90 p. Technical Paper 2001/3.

[61] Benjaminsson J, Nilsson R. Distributionsformer för biogas och naturgas i Sverige. Stockholm, Sweden: Grontmij AB; 2009 Nov. 76 pp.

[62] Hülsbergen K-J, Feil B, Biermann S, Rathke G-W, Kalk W-D, Diepenbrock W. A method of energy balancing in crop production and its application in a long-term fertilizer trial. Agric Ecosyst Environ 2001;86:303–21.

[63] Scholz V, Berg W, Kaulfuß P. Energy balance of solid fuels. J Agric Eng Res 1998;71:263–72.

[64] Achilles A, Achilles W, Brenndörfer M, Einschütz K, Frisch J, Fritzsche S, et al. Betriebsplanung Landwirtschaft 2006/07. Darmstadt, Germany: KTBL; 2006.

[65] Mikkola HJ, Ahokas J. Indirect energy input of agricultural machinery in bioenergy production. Renew Energy 2009; 35(1):23–8.

[66] Börjesson P. Energianalyser av biobränsleproduktion i svenskt jord- och skogsbruk - idag och kring 2015. Lund,

Sweden: Department of Technology and Society, Lund University; 1994. 67 p. IMES/EESS Report No 17.
[67] Bowers W. Agricultural field equipment. In: Fluck RC, editor. Energy in farm production. Amsterdam, The Netherlands: Elsevier; 1992. p. 117–29.
[68] Örebro SJV. Sweden. Personal communication. 2010-10-14.
[69] Overend RP. The average Haul distance and transportation Work factors for biomass delivered to a Central plant. Biomass 1982;2:75–9.
[70] El- SCB. gas- och fjärrvärmeförsörjningen 2009. Stockholm, Sweden: Statistics Sweden; 2010. 24 p. Report No EN 11 SM 1002.
[71] Börjesson P, Berglund M. Environmental systems analysis of biogas systems - Part I: fuel-cycle emissions. Biomass Bioenergy 2006;30(5):469–85.
[72] Energinet dk. Gas in Denmark - Plan for security of natural gas supply. 72 p. Fredericia, Denmark: Energinet.dk, ISBN 978-87-90707-71-2; 2009.
[73] Börjesson P, Gustavsson L. Regional production and utilization of biomass in Sweden. Energy 1996;21(9):747–64.
[74] Hagström P. Biomass potential for heat, electricity and vehicle fuel in Sweden, vol. I. Uppsala, Sweden: Department of Bioenergy, Swedish University of Agricultural Sciences; 2006. 226 p.
[75] Heller MC, Keoleian GA, Volk TA. Life cycle assessment of a willow bioenergy cropping system. Biomass Bioenerg 2003; 25(2):147–65.
[76] Caserini S, Livio S, Giugliano M, Grosso M, Rigamonti L. LCA of domestic and centralized biomass combustion: the case of Lombardy (Italy). Biomass Bioenerg 2010;34(4): 474–82.
[77] Uellendahl H, Wang G, Moller HB, Jorgensen U, Skiadas IV, Gavala HN, et al. Energy balance and cost-benefit analysis of biogas production from perennial energy crops pretreated by wet oxidation. Water Sci Technol 2008;58(9):1841–7.
[78] Scholz V, Heiermann M, Kaulfuss P. Sustainability of energy crop cultivation in Central Europe. In: Lichtfouse E, editor. Sociology, organic farming, climate change and soil Science. Springer; 2010. p. 109–45.
[79] Björklund A, Niklasson T, Wahlén M. Biomass in Sweden: biomass-fired CHP plant in Eskilstuna. Refocus 2001;2(7): 14–8.
[80] De S, Kaiadi M, Fast M, Assadi M. Development of an artificial neural network model for the steam process of a coal biomass cofired combined heat and power (CHP) plant in Sweden. Energy 2007;32(11):2099–109.
[81] Kreuger E, Sipos B, Zacchi G, Svensson S-E, Björnsson L. Bioconversion of industrial hemp to ethanol and methane: the benefits of steam pretreatment and co-production. Bioresour Technol 2011;102(3):3457–65.
[82] Dawson CJ, Hilton J. Fertiliser availability in a resource-limited world: production and recycling of nitrogen and phosphorus. Food Policy 2011;36(Suppl. 1):S14–22.
[83] Schröder JJ, Smit AL, Cordell D, Rosemarin A. Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. Chemosphere 2011; 84(6):822–31.
[84] Ottosson P, Bjurström H, Johansson C, Svensson S-E, Mattsson JE. Förstudie – Halmaska i ett kretslopp. Stockholm, Sweden: Värmeforsk; 2009. 55 p. Report No 1102.
[85] Svensson S-E, Prade T, Hallefält F, Mattsson JE. Utvädering av metoder för vårskörd av stråbränslen. Alnarp, Sweden: Swedish University of Agricultural Sciences (SLU), Department of Agriculture - Farming system, Technology and Product Quality; 2010. 32 p.
[86] Bühle L, Stülpnagel R, Wachendorf M. Comparative life cycle assessment of the integrated generation of solid fuel and biogas from biomass (IFBB) and whole crop digestion (WCD) in Germany. Biomass Bioenergy 2011;35(1):363–73.
[87] Heiermann M, Ploechl M, Linke B, Schelle H, Herrmann C. Biogas Crops-Part I: specifications and Suitability of field crops for anaerobic digestion. Agric Eng Int CIGR 2009;XI:1–17.
[88] Fogelfors H. Växtproduktion i jordbruket. Borås, Sweden: Natur och Kultur; 2001.
[89] Finell M, Xiong S, Olsson R. Multifunktionell industrihampa för norra Sverige. Uppsala, Sweden: Swedish University of Agricultural Sciences (SLU); 2006. 41 pp. BTK Report No 2006:13.

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Industrial hemp as a potential bioenergy crop in comparison with kenaf, switchgrass and biomass sorghum

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ABSTRACT

This study takes combined field trial, lab experiment, and economic analysis approaches to evaluate the potential of industrial hemp in comparison with kenaf, switchgrass and biomass sorghum. Agronomy data suggest that the per hectare yield (5437 kg) of industrial hemp stem alone was at a similar level with switchgrass and sorghum; while the hemp plants require reduced inputs. Field trial also showed that ~1230 kg/ha hemp grain can be harvested in addition to stems. Results show a predicted ethanol yield of ~82 gallons/dry ton hemp stems, which is comparable to the other three tested feedstocks. A comparative cost analysis indicates that industrial hemp could generate higher per hectare gross profit than the other crops if both hemp grains and biofuels from hemp stem were counted. These combined evaluation results demonstrate that industrial hemp has great potential to become a promising regional commodity crop for producing both biofuels and value-added products.

1. Introduction

Biomass conversion to biofuels and chemicals has generated a lot of interests due to the increasing demand for establishing a secure and sustainable energy supply that can be incorporated to the existing fuel system (Shi et al., 2011a). Traditionally, biofuels have been produced based on starchy or sugar crops such as corn, wheat, sugar beets, and sugar cane. Bioethanol derived from lignocellulosic biomass is considered as a promising renewable fuel because of the vast availability and low cost of the feedstocks (Chundawat et al., 2011). However, the major challenges of biofuels production from lignocellulosic biomass include a stable and consistent feedstock supply, development of efficient pretreatment technologies to remove lignin and facilitate enzyme access to the cellulose for sugar release, effective fermentation of sugars and valorization of lignin to value added chemicals (Yang and Wyman, 2008).

Industrial hemp (*Cannabis sativa* L.) has a long history being known and used by humans for a variety of applications, including fibers for cloths and building composites, seed as a source of essential oil and food, and secondary metabolites from hemp for pharmaceutical applications (Linger et al., 2002). In the United States, hemp farming goes back to the eighteenth century; however, industrial hemp became a controversial crop due to its genetic closeness to tetrahydrocannabinol (THC)-producing plants, and was stymied in the 1930s. Growing interests in the commercial cultivation of industrial hemp in the United States resurged since the 1990s. There are multiple, harvestable components of the hemp plant that can be used in diverse ways. Based on a recent report, the current annual sales of hemp based product in the U.S. alone is about $600 million dollars (Johnson, 2017). In the omnibus farm bill debate, the 113th congress made significant changes to the U.S. policies towards industrial hemp. The Agricultural Act ("farm bill", P.L. 113-79) was passed in 2014, which allows certain research institutions and state departments of agriculture to grow industrial hemp. The continuous introduction and clarification on industrial hemp at legislation level promoted industrial hemp related research and allowed for a kaleidoscopic realm of possibilities to be discovered.

The conversion of lignocellulosic biomass to biofuels usually undergoes three steps: (i) pretreatment to open the rigid structure of plant cell walls; (ii) enzymatic saccharification to breakdown solid cellulose into sugars; and (iii) fermentation to produce biofuels or chemicals (Kamireddy et al., 2013). Several pretreatment techniques have been studied over the years, with dilute acid, alkali, hot water, and steam

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explosion, being the most extensively inverstigated (Wyman et al., 2011). However, the efficacy of a pretreatment method largely depends on the selection of biomass feedstock; at the same time, the selection of a pretreatment technology greatly influences biomass decomposition and sugar release (Behling et al., 2016; Yang and Wyman, 2008). Alkali pretreatment using dilute NaOH or lime generally requires lower temperature and pressure, and less residence time compared to other pretreatment methods (Sun and Cheng, 2002). During an alkali pretreatment process, the ester bonds cross-linking between lignin and xylan are typically cleaved, thus increasing the accessibility of cellulose and hemicellulose enriched fractions to enzymatic digestion (Xu et al., 2010). In contrast, dilute sulfuric acid pretreatment solubilizes hemicelluloses, relocates lignin, and thereby disrupts the lignocellulosic composite material linked by covalent bonds, hydrogen bonds, and van der Waals forces (Mosier et al., 2005). Dilute sulfuric acid pretreatment has been shown as a leading pretreatment process that has been implemented at commercial scale (Shi et al., 2011b). The intensity of deconstruction during a pretreatment process depends on the characteristics of the biomass feedstock as well as the pretreatment conditions and the targeted end-products (Yang and Wyman, 2008).

In addition to the existing applications of hemp for fiber, oil and nutraceutical products, one potential application of industrial hemp is for biofuels production. Ethanol production from industrial hemp using a combined dilute acid/stream pretreatment technique was investigated previously (Kuglarz et al., 2014). Results show that pretreatment with 1% sulfuric acid at 180 °C for 10 min led to the highest glucose yield (73–74%) and ethanol yield of 75–79% (0.38–0.40 g-ethanol/g-glucose). In a follow-up study, an ethanol yield of 149 kg of ethanol/dry ton hemp was reported using alkaline oxidative pretreatment (Kuglarz et al., 2016). In another study, hemp hurds were fractionated by organosolv pretreatment for lignin degradation and sugar formation. More than 75% of total cellulose and 75% of total lignin were removed under the following experimental conditions: 165 °C, 3% H_2SO_4, 20 min reaction time, and 45% methanol (Gandolfi et al., 2014). Furthermore, due to its capacity to grow on heavy metal contaminated soil, industrial hemp has shown potential in bioremediation of heavy metals in addition to biofuel production (Kyzas et al., 2015).

Despite the existing studies related to the biofuels potential of industrial hemp, its technical and economic feasibility still remains unclear (Johnson, 2017). It is necessary to understand whether industrial hemp can yield biofuel quantities comparable to the other biomass feedstocks and whether it is economically profitable to grow industrial hemp for biofuels and bioproducts. In order to answer these questions, this study aims to evaluate the potential of industrial hemp as a biofuel crop using a combined agronomic, experimental and economic analysis approach in comparison with kenaf, switchgrass and biomass sorghum. Specific objectives are to: 1) compare the composition and heating value of industrial hemp with other biomass feedstocks; 2) compare the recalcitrance of the four feedstocks upon dilute sulfuric acid or alkali pretreatment and their sugar yields from subsequent enzymatic hydrolysis; 3) compare both theoretical and predicted ethanol yields from all four feedstocks and 4) conduct an economic analysis by integrating agronomy and experimental data to evaluate the economics of industrial hemp as potential biofuels feedstock as compared to the other biomass feedstocks. Results from the first-of-a-kind evaluation demonstrate the great potential of using industrial hemp as a promising regional commodity crop for producing both biofuels and value-added products.

2. Materials and methods

2.1. Feedstocks

Industrial hemp (*Cannabis sativa* L., cv 'Futura 75') and kenaf (*Hibiscus cannabinus*, cv 'Whitten') for this study were seeded at a site with a Maury silt loam (Fine, mixed, active, mesic Typic Paleudalfs; 4.2% organic matter, pH = 6.3) at a research farm, University of Kentucky in June 2015. The research area was prepared by conventional tillage. Nitrogen was applied pre-plant at 55 kg N/ha via urea (46-0-0). No other nutrients, pesticides, or any other inputs were applied throughout the trial. Plots were seeded with an amended plot drill (Almaco; Nevada, Iowa) with 2.4 m effective width in 20 cm rows. Hemp and kenaf were seeded at rates of 66 and 44 kg pure live seed ha^{-1}, respectively. The above ground portions of the plants (at approximately 6 cm above the soil surface) were collected by a hand-held sickle mower 110 days after seeding on 29 Sep 2015. All plant material was dried for 7 days in a forced-air dryer at ambient temperatures and transported to the laboratory for analyses. The yields of cellulosic biomass portion (stem) for hemp and kenaf were 5347 kg/ha and 8227 kg/ha, respectively on dry basis; while yield of the grain portion of hemp was 1230 kg/ha on dry basis. A subsample from the stem was collected, ground to pass a 2 mm sieve using a model 4 Wiley mill, and stored in Ziploc bags at room temperature for subsequent experiments. Switchgrass (*Panicum virgatum*, Alamo) and sorghum (*Sorghum bicolor*, forage variety ES5200) samples were provided by the Bioenergy Feedstock Library, Idaho National Laboratory, Idaho Falls, ID.

2.2. Pretreatment

For dilute alkali pretreatment, 2 g of biomass was mixed with 18 mL of 2 wt% NaOH solution in a tubular reactor (made of stainless steel SS316, 6″ in length and ¾″ in outer diameter). The reactors were then capped and the premixed slurry was soaked at room temperature for 4 h. Pretreatment was conducted at 140 ± 2 °C for 1 h in a temperature controlled oil bath. As a comparison, dilute sulfuric acid pretreatment was carried out at 160 ± 2 °C for 30 min on the four feedstocks. The reaction was performed by adding 18 mL of 1 wt% of H_2SO_4 to 2 g biomass sample, in the same experimental setup as mentioned above. The pretreatment conditions for dilute alkali and acid pretreatment were selected based on previous reports (Shi et al., 2011b; Xu et al., 2010). After pretreatment, the pretreated biomass was washed 4 times with 40 mL deionized (DI) water for each wash and the solids were separated from the liquid by centrifugation at 4000g. The liquid from first wash was collected for sugar analysis. The washed solids were stored at 4 °C for enzymatic hydrolysis.

2.3. Enzymatic hydrolysis

Enzymatic hydrolysis of the four untreated and pretreated biomass were carried out by following the NREL laboratory analytical procedure (Selig et al., 2008). The cellulase (CTec2, Novozymes Inc.) and hemicellulase (HTec2, Novozymes Inc.) enzymes were premixed at a 9:1 v/v ratio. The saccharification was performed at 50 °C for 72 h at an enzyme loading of 10 mg enzyme protein/g starting biomass in an orbital shaker (Thermo Forma 435, Thermo Fisher Scientific Inc., Waltham, MA, US). Liquid samples were taken at 2, 6, 12, 18, 24 and 72 h, centrifuged at 4000 rpm for 10 min and the supernatant was analyzed by high performance liquid chromatography HPLC, (Ultimate 3000, Dionex Corporation, Sunnyvale, CA, US)) equipped with a refractive index detector and Bio-Rad Aminex HPX-87H column and guard column assembly. Product separation was obtained at 50 °C with 5 mM H_2SO_4 as mobile phase at a flow rate of 0.4 mL/min to measure fermentable sugar (glucose and xylose) contents.

2.4. Analytical methods

Acid soluble lignin (ASL), acid insoluble lignin (AIL), and carbohydrate content in the untreated feedstocks were determined using the procedure described by NREL (Sluiter et al., 2008). Monomeric sugars including glucose, xylose and arabinose in the untreated biomass and pretreatment and enzymatic hydrolysates were determined via HPLC. The calorific value of biomass was measured using a LECO AC600 bomb calorimeter according to the standard ASTM D5865-10a (ASTM, 2010).

To evaluate the changes in lignin molecular weight distribution during the pretreatment, size exclusion chromatography (SEC) were performed on the lignin streams in untreated and pretreated biomass samples. Lignin in the untreated sample was isolated and extracted by cellulolytic enzyme lignin (CEL) isolation method (Yoo et al., 2016). Lignin precipitated from dilute alkali pretreatment liquid and lignin in the solids after dilute acid pretreatment were prepared by following acetylation method (Lu and Ralph, 1997). The acetylated lignin was then dissolved in Tetrahydrofuran (THF) and stored at room temperature before analysis. The molecular weight distributions, including weight-average molecular weight (M_w) and number-average molecular weight (M_n) of prepared lignin, were measured by an Ultimate 3000 HPLC system (Dionex Corporation, Sunnyvale, CA) equipped with an Ultra Violet (UV) detector and a Mixed-D PLgel column (5 µm particle size, 300 mm × 7.5 mm i.d., linear molecular weight range of 200–4,00,000 u, Polymer Laboratories, Amherst, MA) at 80 °C using a mobile phase of THF at a flow rate of 0.5 mL min^{-1}. Elution profile of materials eluting from the column was monitored at 290 nm and the chromatography was calibrated using polystyrene standards (Sigma-Aldrich).

Fourier transform infrared spectroscopy (FTIR) was performed by using a Thermo Nicolet Nexus 870 FTIR ESP. Samples were pressed to 12 psi using a spring loaded jack onto the ATR crystal. Sample spectra were obtained using an average of 64 scans between 400 and 4000 cm^{-1} with a spectral resolution of 1.928 cm^{-1}. The raw FTIR spectra were baseline corrected and normalized using Omnic 6.1a software and compared in the range 750–2000 cm^{-1}.

2.5. *Statistical analysis*

All experiments were conducted in triplicate or duplicate and the data are presented as mean values and standard deviations. The statistical analysis was performed using SAS® 9.4 (SAS Institute, Cary, NC, US), with a significance level of $P < 0.05$ for all the experimental data.

2.6. *Preliminary economic analysis*

The economic feasibility of the four crops (kenaf, hemp, switchgrass and sorghum) as potential biofuels feedstocks were preliminarily evaluated by considering their biomass yields, growing cost, corresponding ethanol yields, and grain yield and prices. For simplicity, the capital and processing cost to produce ethanol from kenaf, hemp, switchgrass and sorghum including the feedstock cost were assumed same at this stage considering their similar process conditions. And these costs were decoupled from the evaluation in this study by assuming a minimum ethanol selling price of $2/gallon (Tao et al., 2011). Overall revenue includes profits from both biomass and grain if applicable. Biomass revenue was obtained from biomass yield multiplying ethanol yield and subtracting growing cost, while the grain revenue was calculated by grain yield and price.

For sensitivity analysis, low and high biomass yields were set to be 25% lower or higher than that of the baseline yield, respectively, in order to demonstrate their effects on revenue based on the theoretical ethanol yield of each feedstock. The overall revenue of kenaf, hemp and switchgrass were calculated only from cellulosic biomass portion of the feedstocks, while sorghum's value included those from both the biomass and grain.

3. Results and discussion

3.1. *Composition analysis and heating values*

Table 1
Chemical composition and heating values of biomass feedstocks.†

	Hemp	Kenaf	Switchgrass	Sorghum
Glucan, %	^{b}36.5 ± 0.6	^{a}40.8 ± 0.3	^{c}34.3 ± 0.1	^{c}35.2 ± 0.1
Xylan, %	^{c}17.0 ± 0.2	^{d}15.6 ± 0.1	^{a}22.9 ± 0.2	^{b}22.1 ± 0.1
AIL, %	19.2 ± 0.0	17.3 ± 0.0	17.5 ± 0.0	16.1 ± 0.2
ASL, %	2.6 ± 0.1	3.0 ± 0.6	2.6 ± 0.0	2.2 ± 0.0
Total Lignin, %	^{a}21.9 ± 0.2	^{b}20.3 ± 0.6	^{b}20.1 ± 0.0	^{c}18.3 ± 0.1
Extractives, %	13.3 ± 0.9	13.0 ± 0.7	12.3 ± 0.2	15.6 ± 0.7
Other, %	11.3 ± 1.6	10.3 ± 0.1	10.5 ± 0.1	8.8 ± 0.4
HHV, MJ/kg	19.24	19.23	18.79	18.33
LHV, MJ/kg	15.82	15.89	15.70	15.24
Moisture Content, %	8.4 ± 1.4	6.8 ± 0.4	6.3 ± 0.6	8.0 ± 0.5

The superscript letters "abcd" indicate the significance levels of the means across feedstocks.

† Compositions and heating values reported are based on the dry weight of untreated biomass.

Table 1 shows the composition analysis and heating value of the four biomass feedstocks. Industrial hemp (stem) contains 36.5% glucan, which is higher ($p < 0.05$) than switchgrass (34.3%), sorghum (35.2%), but lower ($p = 0.006$) than kenaf (40.8%). However, xylan content of industrial hemp (17.02%) is only higher ($p = 0.002$) than kenaf (15.6%) but lower ($P < 0.005$) than switchgrass (22.9%) and sorghum (22.1%). Similar glucan and xylan contents for hemp stem have been reported previously (Kreuger et al., 2011). When both glucan and xylan were summed up, the four feedstocks show similar level of total sugars of ~53–57%. Overall, results illustrate that the availability of fermentable sugars in hemp is comparable to the other three feedstocks.

Lignin is one of the main building blocks of plant cell walls; and depending on biomass type, it accounts for approximately 10–30% of the biomass together with cellulose, hemicellulose and other minor components. Lignin provides structural support and resistance against microbial and oxidative stresses to the plant (Davin and Lewis, 2005). As the second most abundant terrestrial biopolymer on earth, lignin can be converted to aromatic compounds for fuels and chemicals (Prado et al., 2016). Interestingly, hemp has higher ($p = 0.001$) lignin content of 21.9% in comparison to 20.3%, 20.1% and 18.3% lignin in kenaf, switchgrass, and sorghum, respectively. High lignin content in hemp represents a potential opportunity in terms of making platform chemicals to improve profitability from a bio-refinery standpoint (Beckham et al., 2016). A wide range of products can be made out of lignin including phenols, activated carbons, binders, composites, resins, antioxidants, antimicrobial agent, and biomedical materials, carbon fibers, fuels, plastic materials and sorbents (Behling et al., 2016).

Furthermore, calorimetric analysis suggested that hemp (stem) had a similar heating value (HHV) of 19.24 MJ/kg when compared to kenaf (19.23 MJ/kg); whereas both were slightly higher than that of switchgrass (18.79 MJ/kg) and biomass sorghum (18.33 MJ/kg). The slight increase in HHV could be linked to the slightly higher lignin content in industrial hemp as compared to the other feedstocks. Extractives mainly consist of free sugars, alditols, organic acids and inorganic ions; percentages of extractives in hemp were comparable to kenaf and switchgrass but less than sorghum (Templeton et al., 2010). In addition, the other unaccounted components, mainly protein and ash, ranged from 8.8 to 11.3 of the four tested biomass (Chen et al., 2010). Take altogether, the comparative composition and calorimetry analysis demonstrated that hemp is a promising candidate for biofuels production when compare side by side with other biomass feedstocks.

3.2. *Sugar yield from pretreatment and enzymatic hydrolysis*

Sugar release was tracked during pretreatment and enzymatic hydrolysis of the four biomass feedstocks in order to investigate the effectiveness of the two different pretreatment methods on tested feedstocks. Fig. 1A and B show glucose and xylose yield (% of maximum potential based on starting material) from enzymatic hydrolysis of dilute-NaOH (referring to dilute alkali pretreatment thereafter)

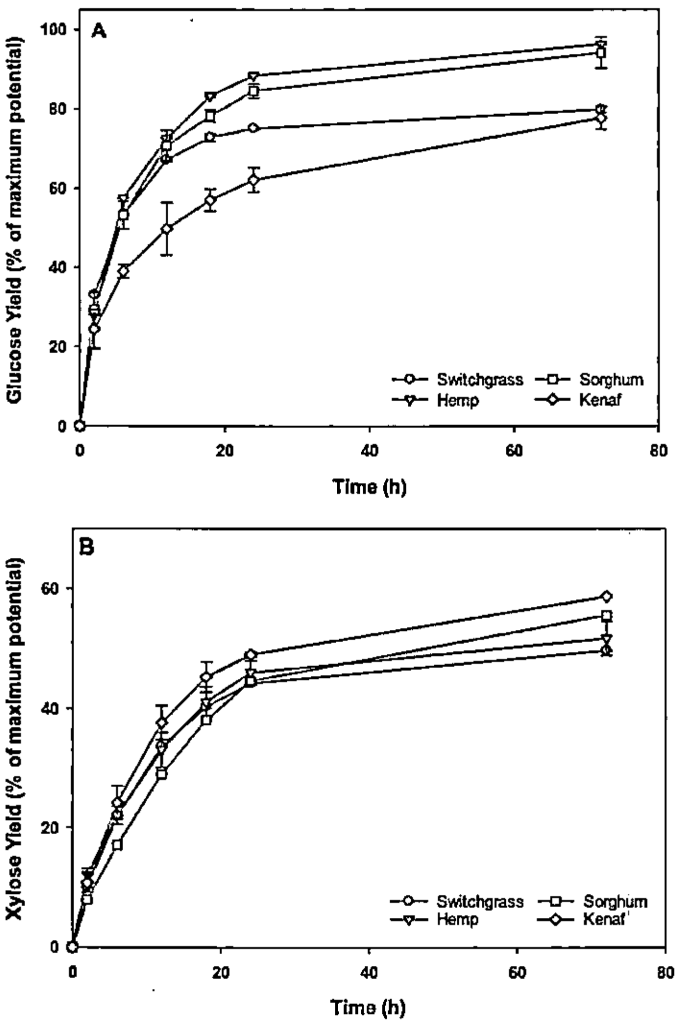

Fig. 1. A) Glucose and B) xylose yield from enzymatic saccharification of dilute alkali pretreated biomass feedstocks at an enzyme loading of 10 mg enzyme protein/g starting biomass.

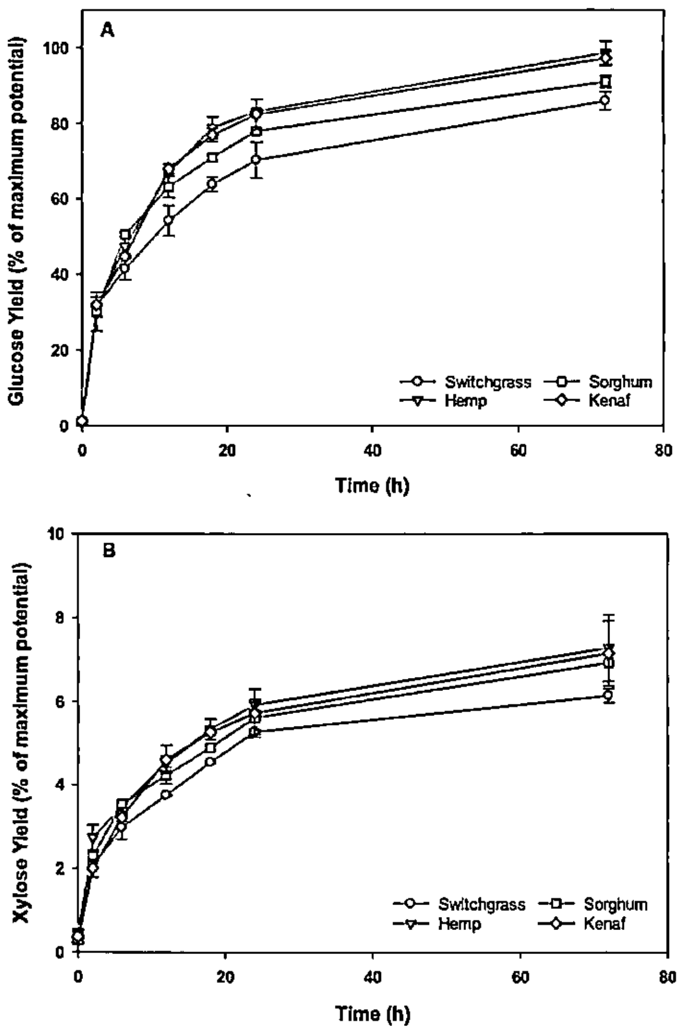

Fig. 2. A) Glucose and B) xylose yield from enzymatic saccharification of dilute acid pretreated biomass feedstocks at an enzyme loading of 10 mg enzyme protein/g starting biomass.

pretreated solids. Results show that glucose and xylose yields for dilute alkali pretreated hemp were 96.3% and 51.7% of the theoretical value, similar to glucose and xylose yields (94.1% and 55.6%, respectively) obtained from sorghum. However, enzymatic hydrolysis of dilute alkali pretreated switchgrass and kenaf led to lower glucose yields, 79.9% and 77.8%, respectively. Xylose yields for switchgrass and kenaf, 49.7% and 58.7%, respectively, were similar to measured yields for hemp and sorghum. Results obtained from this study are comparable to that reported by Xu and colleagues (2010), where under the best pretreatment conditions (50 °C, 12 h, and 1.0% NaOH), glucose and xylose yields from switchgrass reached 74.4 and 62.8%, respectively. In a separate study (Karp et al., 2015), dilute alkali pretreatment of switchgrass at a NaOH loading of 140 mg NaOH/g dry switchgrass and 0.2% anthraquinone at 160 °C and 140 mg NaOH/g dry switchgrass showed ~80% conversion of glucan and xylan within 48 h during enzymatic hydrolysis performed at 10 mg/g of CTec3 and HTec3. For kenaf, a previous study (Ooi et al., 2011) showed 94% of glucose yield using acid pretreatment with 37.5% hydrochloric acid in the presence of $FeCl_3$ at 50 °C or 90 °C. However, 96–100% glucose conversion can be achieved during enzymatic hydrolysis only when the kenaf samples were treated with 25% sodium hydroxide at room temperature (Ruan et al., 2012). In another study, Cao et al. investigating the performance of different pretreatment methods on sorghum, including dilute NaOH, high concentration NaOH, and dilute NaOH plus H_2O_2 (alkaline peroxide) pretreatment (Cao et al., 2012). Among those, the best result of 74.3% cellulose hydrolysis yield was obtained when sweet sorghum bagasse was pretreated by dilute-NaOH solution autoclaving and H_2O_2 immersing pretreatment. Based on results from this study, dilute alkali pretreatment (2% w/v NaOH at 140 ± 2 °C for 1 h) was highly effective on pretreating hemp and sorghum, while less effective on switchgrass and kenaf. It seems that dilute alkali pretreatment could be further optimized for switchgrass and kenaf, probably at a more severe condition, in order to ensure high sugar yields.

Fig. 2A and B show glucose and xylose yield (% of maximum potential based on starting material) from enzymatic hydrolysis of dilute acid pretreated solids, both at 10 mg/g of enzyme loading. Dilute acid pretreatment led to a glucose yield of 98.7% and xylose yield of 7.2% for hemp on basis of the sugar availability in untreated biomass. Similar levels of sugar yields were observed on the other three biomass feedstocks. The low xylose yield for enzymatic hydrolysis of dilute acid pretreated biomass was due to the fact that the majority of the xylan has been removed during dilute acid pretreatment (Shi et al., 2011b). Glucan and xylan recoveries based on raw biomass were summarized for different liquid streams of pretreatment and enzymatic hydrolysis, along with the data showing in Figs. 1 and 2, to provide insights on how pretreatment affects yield of fermentable sugars. Indeed, most of the xylose (~40–66%) was solubilized during dilute acid pretreatment. The glucose yield obtained in this study was higher than a previous report (Kuglarz et al., 2016) where hemp was pretreated by alkaline oxidation with 3% H_2O_2 at 90 °C for 1 h with a yield of 74.8% of glucose after 48 h of hydrolysis. However, when the pretreatment time was increased to 2 h, glucose yield increased to 82.4%. For switchgrass, maximum total glucose and xylose yields of about 86% were achieved at pretreatment conditions of 140 °C for a 40 min reaction time, 160 °C for

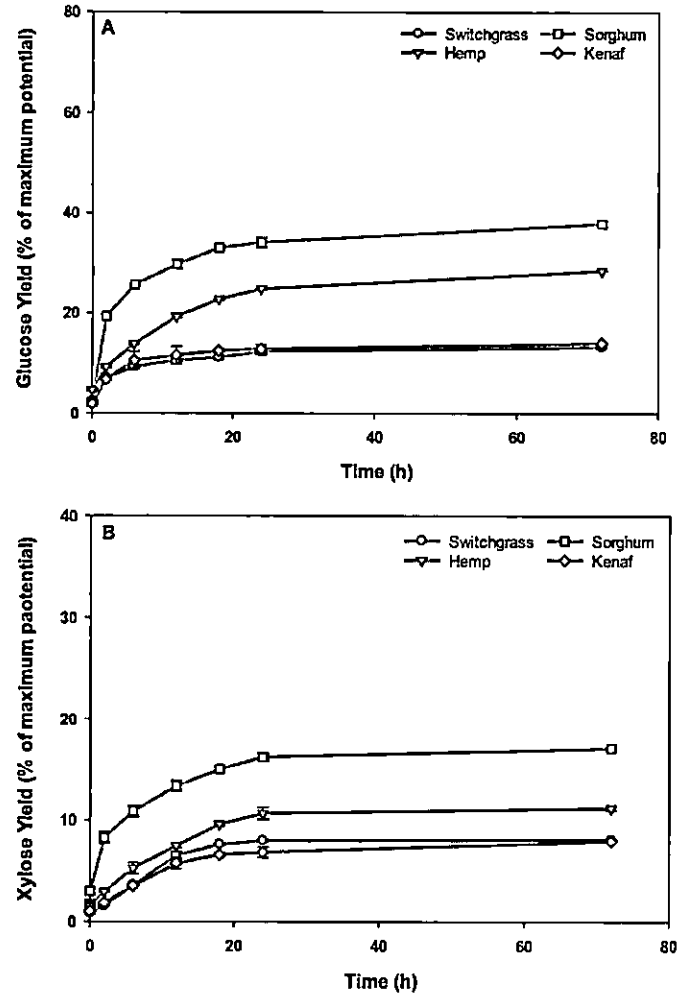

Fig. 3. A) Glucose and B) xylose yield from enzymatic saccharification of untreated biomass feedstocks at 10 mg/g enzyme loading.

10 min, and 180 °C for 2.5 min, with a sulfuric acid concentration of 1.0% (Shi et al., 2011b). In another study, dilute acid pretreatment (1.8% w/v of H_2SO_4 at 121 °C for 1 h) was shown effective at pretreating wild-type forage sorghum and reduced lignin content mutations (Dien et al., 2009). Overall, results from this study indicate that dilute acid pretreatment was as effective as dilute alkali pretreatment on sugar yield from industrial hemp and sorghum. However, dilute alkali pretreatment conditions for switchgrass and kenaf need to be further optimized to ensure high sugar yields. In summary, both dilute alkali and acid pretreatments greatly improved the sugar yield from enzymatic hydrolysis as compared with untreated biomass (Fig. 3A and B). Results from the enzymatic hydrolysis demonstrate that industrial hemp yields similar levels of glucose and xylose, if not higher in some instances, when directly compared to the other biomass feedstocks under the same pretreatment conditions.

3.3. Theoretical and predicted bioethanol yields

Another factor considered to be a determinant of hemp's biofuel potential is whether it can yield an amount of biofuels such as ethanol comparable to other biomass feedstocks. The theoretical ethanol yield and 85% of the theoretical yield based on the composition of the biomass can be seen in Fig. 4A. Theoretical ethanol yields from glucose for hemp, kenaf, switchgrass, and sorghum were 68.2, 75.7, 64.4, and 66.3 gallons/dry ton biomass, respectively. Theoretical ethanol yields from xylose for hemp, kenaf, switchgrass, and sorghum were 33.1, 31.1, 44.7, and 42.8 gallons/ dry ton of biomass, respectively. Combined theoretical ethanol yields from both glucose and xylose for hemp, kenaf, switchgrass, and sorghum were 101.2, 106.8, 109.1, and 109.0 gallons/dry ton of biomass, respectively. Considering a more realistic yield at 85% of the theoretical ethanol yield, about 86.0, 90.8, 92.7, and 92.7 gallons/dry ton of biomass can be produced from hemp, kenaf, switchgrass, and sorghum, respectively. The convertibility of sugars recovered from pretreatment liquid and enzymatic hydrolysate to bioethanol has been evaluated in a number of literatures. In this study, we hydrolyzed pretreated biomass using cellulase and hemicellulases by following typical enzyme loading and conditions to provide a more realistic sugar yields for ethanol yields prediction (Wyman et al., 2011). The recovered sugars can be further fermented to ethanol using a range of wild-type or engineered microbes such as yeast, *E. coli*, or *Z. mobilis*, etc. However, other factors, including presence inhibitors in pretreatment and enzymatic hydrolysate, the microbial strains and the fermentation configuration, may affect the ethanol yield (Shi et al., 2011a). Detoxification techniques and fermentation configurations have been evaluated for the dilute acid and alkali pretreatment technologies in previous studies (Lau and Dale, 2009; Tao et al., 2011).

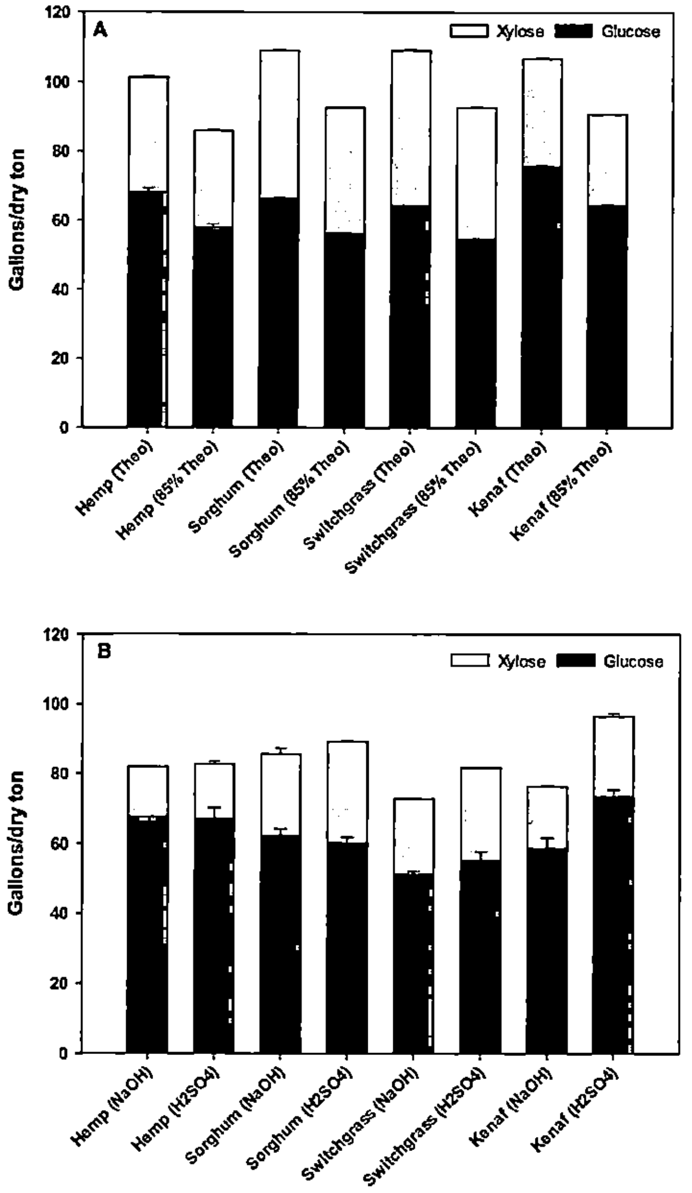

Fig. 4. Ethanol yield based on A) the composition and B) the sugar yields from enzymatic hydrolysis of the pretreated biomass.

Theoretical ethanol yields based on the actually sugar yields of hemp, kenaf, switchgrass, and sorghum using two pretreatment methods were compared (Fig. 4B). For dilute alkali pretreatment, combined theoretical ethanol yields from both glucose and xylose were

82.1, 76.5, 73.0, and 85.8 gallons/dry ton of biomass, for hemp, kenaf, switchgrass, and sorghum, respectively. However, combined theoretical ethanol yields (counting xylose in pretreatment liquid) for dilute acid pretreatment were 82.8, 96.6, 82.0, and 89.5 gallons/ dry ton of biomass for hemp, kenaf, switchgrass, and sorghum, respectively. The predicted ethanol yields represent 70–90% of the theoretical yields (Fig. 4A). For instance, the predicted ethanol yields for hemp were 81% and 82% for dilute alkali and dilute acid pretreatment, respectively, which are comparable to the scenarios reported elsewhere. In one scenario, Sipos and co-workers reported 71–74% ethanol yield from steam explosion pretreated (2% SO_2 at 210 °C for 5 min) dry and ensiled industrial hemp (Sipos et al., 2010). In another study, hemp hurds were converted to ethanol via steam pretreatment (for 10 min at 210 °C), reaching a maximum ethanol yield of 70% (Barta et al., 2010). It should be noted that the ethanol yields reported in the literature did not include the potential ethanol from xylose as the strain (yeast) that was tested can only ferment six carbon sugars. However, both hexose and pentose sugars can be potentially co-fermented using engineered strains of yeast and bacteria capable of utilizing both (Lau and Dale, 2009). Thus, the combined ethanol yields were used for the economic analysis in this study. Overall, it can be concluded that industrial hemp was able to stand its own in direct comparison to kenaf, switchgrass, and sorghum and has similar bioethanol potential as the other biomass feedstocks.

3.4. FTIR and GPC characterization

The structural and chemical changes in the dilute alkali and acid pretreated samples as compared with untreated feedstocks were investigated by FTIR. Seven peaks were used as references to monitor the chemical changes of lignin and carbohydrates. The peaks at 1510 cm^{-1} and 1329 cm^{-1} represent the aromatic skeleton of lignin and the syringyl and guaiacyl condensed lignin, respectively; no significant change was observed at 1329 cm^{-1}, whereas the intensity of 1510 cm^{-1} decreased for dilute alkali pretreated biomass when compared to untreated and dilute acid pretreated samples, indicating lignin removal during alkali pretreatment. The peak at 900 cm^{-1} represents amorphous cellulose while the peak at 1098 cm^{-1} refers to C–O vibration of the crystalline region. When compared with untreated biomass, peak intensity at 1098 cm^{-1} for dilute acid pretreated samples increased, indicating the increase of crystallinity by removing amorphous hemicellulose during dilute acid pretreatment (Li et al., 2010). Furthermore, the bands at 1056 cm^{-1}, 1235 cm^{-1}, and 1375 cm^{-1}, corresponding to C–O stretch in cellulose and hemicellulose, C–O stretching in lignin and hemicellulose, and C–H deformation in cellulose and hemicellulose, respectively, showed significant decreases in dilute alkali pretreated biomass, which aligns with the removal of both hemicellulose and lignin during dilute alkali pretreatment (Gupta and Lee, 2010). Taken together, results clearly indicate that both dilute acid and alkali pretreatment can effectively break down the cell wall polymeric matrix by selective removal of hemicelluloses and/or lignin.

To get a better insight to lignin depolymerization during dilute alkali and acid pretreatment, molecular weight distributions of the residual lignin for all the feedstocks were estimated by GPC (Table 2). For untreated biomass, switchgrass had the highest average molecular weight (M_w) of 7541 g/mol; while sorghum had the lowest M_w of 6109 g/mol. The M_w of the recovered lignin streams from dilute alkali and acid pretreatment liquid, decreased 8–44% as compared to that of untreated biomass, indicating partial lignin depolymerization during the pretreatment. The M_w and number-average molecular weight (M_n) of lignin streams in the dilute acid pretreated solids remained the same or slightly increased as compared to the M_w and M_n for lignin steams in untreated biomass. Additionally, the polydispersity index (PDI) of the lignin in pretreated samples for sorghum, switchgrass and kenaf increased when comparted to untreated biomass, indicating a wide span of molecular weight distribution after pretreatment.

3.5. Preliminary economic analysis

Biomass yields, growing costs, and the corresponding ethanol yields (both theoretical and predicted ethanol yields based on experimental data) are applied to evaluate the economics for the four biomass types examined as potential biofuel feedstocks here. Kenaf is a warm season fiber crop which possess high growth rate and ready for harvesting in 4–5 months (Saba et al., 2015). Kenaf is regarded as the alternative source of energy which consist of a core (65%) and bast fibers (35%); its yield varies widely, from 5600 kg/ha at northern to 33,600 kg/ha southern in the United States (Geisler, 2015; Lee, 2014; LeMahieu et al., 1991). A kenaf yield of 8227 kg/ha was obtained in this study from a research plot at the University of Kentucky. The experimental ethanol yield of kenaf using dilute acid pretreatment in this study is 96.5 gallons/dry ton (Fig. 4B). The growing cost of kenaf including pre-harvest variable costs, custom harvest and hauling costs, and fixed costs was set as $724/ha according to a production scenario done in Kentucky at 2013 (Lee, 2014). Therefore, at a price of $2/gallon of ethanol, a revenue of $908 per ha from kenaf as biofuel feedstock can be achieved based on dilute acid pretreatment (Table 3).

In the past, industrial hemp can be grown for its fiber, seed or as a dual-purpose crop. Similar with kenaf, the variation in hemp yield is significant ranging from 2 to 18 ton/ha (Kuglarz et al., 2014; Robbins et al., 2013; USDA, 2000). The biomass yield for fiber-only is approximately twice the yield of dual system for fiber and seed mainly due to the degradation of fiber quality of male plants over time (Robbins et al., 2013). However, since the quality requirement for ethanol production is different from the one for fiber application, it is feasible to grow hemp as a dual purpose crop, hemp biomass for biofuels and seed for oil or chemicals. The yields of hemp biomass and seed cultivated in this study as described in Materials and Methods are 5347 kg/ha and 1231 kg/ha, respectively. The experimental ethanol yield of hemp using dilute acid pretreatment is 82.3 gallon/dry ton (Fig. 4B). The growing cost of hemp is assumed to be the same as with kenaf, at $724/ha in this preliminary analysis, considering their similar growing process such as timing, equipment, and fertility. This gives a revenue of $170 per ha from hemp biomass only. In addition, the average price for industrial hemp seed was between $1.98/kg and $2.20/kg in 2011 (Hansen, 2015). The revenue from hemp seed could be $2462/ha at a hemp seed price of $2.0/kg. Therefore, the overall revenue from industrial hemp could be $2632/ha (Table 3).

Table 2
The molecular weight distribution of lignin streams comparing untreated biomass with dilute acid pretreated and dilute alkali pretreated biomass.[1]

	Untreated			Dilute alkali–liquid stream			Dilute acid–solid stream		
	M_w	M_n	PDI	M_w	M_n	PDI	M_w	M_n	PDI
Hemp	6771	2530	2.7	5529	2478	2.2	5559	2541	2.2
Sorghum	6109	4216	1.4	3366	1686	2.0	3683	1813	2.0
Switchgrass	7541	4122	1.8	4215	1917	2.2	4504	2118	2.1
Kenaf	6944	3259	2.1	6148	2591	2.4	6350	2692	2.4

[1] M_w: weight average molecular weight; M_n: number-average molecular weight; PDI: polydispersity index.

Table 3
Revenue and cost for growing of kenaf, hemp, switchgrass and sorghum based on dilute acid and dilute alkali pretreatment.[1]

	Biomass yield	Grain yield	Growing cost	Grain price	Revenue grain	Ethanol yield		Overall revenue (biomass and grain)	
						Actual	Theoretical	Actual	Theoretical
	kg/ha	kg/ha	$/ha	$/kg	$/ha	gal/dry ton		$/ha	
Kenaf	8227	–	724	–	–	96.5 (76.5)	107	908 (570)	1085
Hemp	5347	1231	724	2.0	2462	82.3 (82.1)	101	2632 (2625)	2981
Switchgrass	7000	–	463	–	–	82.0 (73.0)	109	803 (664)	1235
Sorghum	9070	4800	598	0.14	666	89.5 (85.8)	109	1725 (1656)	2105

[1] Values in the parenthesis are for dilute alkali pretreatment.

Field trials research has been conducted on switchgrass as a potential feedstock for biofuel production (Mitchell et al., 2016; Perrin et al., 2008). Site-specific annualized yields from the 5-year period ranged widely from 2500 to 9000 dry matter kg/ha (Perrin et al., 2008). A yield of 7000 kg/ha was the ten average by extrapolation, which is used in this study. Based on the five-year average of 10 farms in Nebraska, South Dakota, and North Dakota, the growing cost at a farm gate was $463/ha (at 7000 kg/ha), which includes all expenses plus land costs and labor (Perrin et al., 2008). With an ethanol yield of 82 gallon/ton using dilute acid pretreatment, growing switchgrass can generate a revenue of $803/ha (Table 3).

Based on final usage, sorghum has various cultivars, grain sorghum, forage sorghum, biomass sorghum and sweet sorghum. Different cultivars have different yields for grain and forage. In this study, grain sorghum is used for comparison since sorghum is one of the main food sources (USDA, 2016). The average grain yield of grain sorghum across United States is 4800 kg/ha in 2015 (USDA, 2016); and the price is $0.14/kg (Missouri, 2015). On the other hand, the average forage yield from forage sorghum is 14.6 ton/ha in 2015 (USDA, 2016). Considering the lower yield of forage from grain sorghum than from forage sorghum, the forage yield from grain sorghum was assumed at 10 ton/ha, a 31.5% decrease. Then, the overall revenue from grain sorghum would be $1725/ha with an ethanol yield of 89.5 gallon/ton using dilute acid pretreatment (Table 3).

The overall revenues for four biomass pretreated with dilute alkali showed comparable results. Hemp achieved the highest overall revenue of $2625/ha based on currently available ethanol yield, followed by sorghum ($1656/ha), switchgrass ($664/ha) and kenaf ($570/ha). Based on theoretical ethanol yield, the revenues followed the same order, hemp having the highest of $2981/ha and kenaf with lowest of $1085/ha. Among the overall revenue of hemp, 94% is from hemp seed, which was mainly resulted from two factors: one is that the growing cost was only applied to biomass revenue as described in Methods; second is the low biomass yield for hemp in this study, 5347 kg/ha, which may be due to the variety used in this study. In contrast, Robbins et al. reported a potential medium and high yield of 14,231 kg/ha and 18,154 kg/ha, respectively, for fiber only in Kentucky, USA (Robbins et al., 2013) and Kuglarz reported a yield of 12,400 kg/ha in Europe (Kuglarz et al., 2014) from an experimental farm land. If a hemp yield of 14,231 kg/ha is used, a revenue of $1636/ha could be achieved from hemp biomass only using dilute alkali pretreatment, which is still the highest revenue of the four biomass feedstocks examined here. This yield is used as a baseline of hemp for sensitivity analysis as shown in Table 4. The harvesting time and cultivation practice may affect the yield of hemp biomass and ethanol, which will be investigated in future work.

Considering the widely varying crop yields, a sensitivity analysis about yield on revenue was investigated by varying yield 25% lower or higher than that of baseline (Table 4). The theoretical ethanol yields were applied for simplicity and potentials. The revenue of kenaf, hemp and switchgrass were only from biomass, while sorghum's value included those from both biomass and grain. As shown in Table 4, hemp and sorghum exhibited very close revenues, about $2100/ha ($330/ton biomass treated) at medium yield, which are approximately 90% and 70% higher than those of kenaf and switchgrass, respectively. According to DOE's billion ton target, the target biomass price is $84/ton at 2020 (Langholtz et al., 2016). If the capital and operating cost is three times the cost of biomass, there could be a positive profit from growing hemp for biofuels production.

Table 4
Sensitivity analysis of effect of crop yield on revenue of kenaf, hemp, switchgrass and sorghum with theoretical ethanol yield.

	Revenue at theoretical ethanol yield ($/ha)[2]		
	Low yield	Medium	High yield
Kenaf	632	1085	1537
Hemp[1]	1432	2150	2869
Switchgrass	810	1235	1659
Sorghum	1596	2105	2614

[1] Assuming a medium biomass yield of hemp at 14,231 kg/ha (Robbins et al., 2013).
[2] Revenue from kenaf, hemp and switchgrass are only from biomass, while revenue for sorghum from both biomass and grain.

A 25% change in hemp yield caused a 33% variation in final revenue, which is same for switchgrass. Kenaf demonstrated a higher fluctuation in revenue (42%), while the sorghum the lowest (24%). At high yield scenario, hemp exhibited a revenue of $2896 kg/ha ($456/ton biomass), which would significantly increase the economic feasibility of growing industrial hemp. Detailed techno-economic analysis will be conducted in future research.

In this study, we investigated a dual purpose scenario where the hemp stem is used to produce biofuel and hemp grain is sold to the market for value-added co-products. However, in order to maximize the profit from hemp cultivation, other scenarios could be explored. In one scenario, separating fiber from stem adds more value to the hemp economics, and hemp hurds can be utilized for biofuel production. Composition of hemp hurds varies depending on the retting process; however, the composition has been reported comparable to that of hemp stem (Barta et al., 2010). More value can be extracted from hemp grain owing to the potential for producing a wide range of essential oils and food products. Hemp seed oil is a rich source of omega-3 fatty acids which are essential dietary supplements. In addition, hemp oil contains several natural products, including β-caryophyllene, myrcene, β-sitosterol, α/γ-tocopherol, and methyl salicylate etc. If extracted and purified, these compounds can be at much higher value in pharmaceutical and nutrition markets (Leizer et al., 2000).

The fiber portion of industrial hemp has been explored as a feedstock for making composite materials for building application such as multi-layer wall plug for concrete, steel or wood structures (Sassoni et al., 2014). Furthermore, in a recent study, hemp stem and hurds have been successfully converted to advanced materials for energy-related applications such as supercapacitors and carbon spheres (Sun et al., 2016). There are trade-offs between fuels, materials and essential oils, and pharmaceutical applications from hemp; achieving all potential product streams simultaneously form hemp plants is unlikely. Hence, an optimized harvesting strategy should be determined that would improve the overall economics of hemp-based fuels and bioproducts. In addition, a comprehensive techno-economic analysis considering other value-added products from industrial hemp, as well as taking account the agronomy practices such as harvesting and preprocessing will give a deeper insight to hemp's real potential.

4. Conclusions

The potential of converting industrial hemp for biofuels and bioproducts in comparison with other biomass feedstocks was evaluated. Dilute acid pretreatment was more effective in term of sugar yield from enzymatic hydrolysis when compared with dilute alkali pretreatment. Cost analysis indicates that industrial hemp could generate higher per hectare gross profit than the other crops. In summary, hemp has great potential to become a promising commodity crop for producing both biofuels and value-added products that can improve the stigma surrounding its applications. Future research will extend the preliminary techno-economic analysis to incorporate harvesting, preprocessing, conversion and the other hemp derived coproducts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2017.08.008.

References

ASTM D5865-10a, 2010. Standard Test Method for Gross Calorific Value of Coal and Coke. American Society for Testing and Materials (ASTM) International, West Conshohocken, PA, USA.

Barta, Z., Oliva, J., Ballesteros, I., Dienes, D., Ballesteros, M., Réczey, K., 2010. Refining hemp hurds into fermentable sugars or ethanol. Chem. Biochem. Eng. Q. 24 (3), 331–339.

Beckham, G.T., Johnson, C.W., Karp, E.M., Salvachúa, D., Vardon, D.R., 2016. Opportunities and challenges in biological lignin valorization. Curr. Opin. Biotechnol. 42, 40–53.

Behling, R., Valange, S., Chatel, G., 2016. Heterogeneous catalytic oxidation for lignin valorization into valuable chemicals: what results? What limitations? What trends? Green Chem. 18 (7), 1839–1854.

Cao, W., Sun, C., Liu, R., Yin, R., Wu, X., 2012. Comparison of the effects of five pretreatment methods on enhancing the enzymatic digestibility and ethanol production from sweet sorghum bagasse. Bioresour. Technol. 111, 215–221.

Chen, S.-F., Mowery, R.A., Sevcik, R.S., Scarlata, C.J., Chambliss, C.K., 2010. Compositional analysis of water-soluble materials in switchgrass. J. Agric. Food. Chem. 58 (6), 3251–3258.

Chundawat, S.P., Beckham, G.T., Himmel, M.E., Dale, B.E., 2011. Deconstruction of lignocellulosic biomass to fuels and chemicals. Annu. Rev. Chem. Biomol. Eng. 2, 121–145.

Davin, L.B., Lewis, N.G., 2005. Lignin primary structures and dirigent sites. Curr. Opin. Biotechnol. 16 (4), 407–415.

Dien, B.S., Sarath, G., Pedersen, J.F., Sattler, S.E., Chen, H., Funnell-Harris, D.L., Nichols, N.N., Cotta, M.A., 2009. Improved sugar conversion and ethanol yield for forage sorghum (Sorghum bicolor L. Moench) lines with reduced lignin contents. Bioenergy Res. 2 (3), 153–164.

Gandolfi, S., Ottolina, G., Consonni, R., Riva, S., Patel, I., 2014. Fractionation of hemp hurds by organosolv pretreatment and its effect on production of lignin and sugars. ChemSusChem 7 (7), 1991–1999.

Geisler, M., 2015. Kenaf. http://www.agmrc.org/commoditiesproducts/fiber/kenaf. (Last accessed, April 21th, 2017).

Gupta, R., Lee, Y., 2010. Investigation of biomass degradation mechanism in pretreatment of switchgrass by aqueous ammonia and sodium hydroxide. Bioresour. Technol. 101 (21), 8185–8191.

Hansen, R., 2015. Industrial Hemp, vol. 2017. http://www.agmrc.org/commodities-products/fiber/industrial-hemp. (Last accessed, April 21th, 2017).

Johnson, R., 2017. Hemp as an agricultural commodity, (Ed.) C.R. Service. https://fas.org/sgp/crs/misc/RL32725.pdf. (Last accessed, April 21th, 2017).

Kamireddy, S.R., Li, J., Abbina, S., Berti, M., Tucker, M., Ji, Y., 2013. Converting forage sorghum and sunn hemp into biofuels through dilute acid pretreatment. Ind. Crops Prod. 49, 598–609.

Karp, E.M., Resch, M.G., Donohoe, B.S., Ciesielski, P.N., O'Brien, M.H., Nill, J.E., Mittal, A., Biddy, M.J., Beckham, G.T., 2015. Alkaline pretreatment of switchgrass. ACS Sustain. Chem. Eng. 3 (7), 1479–1491.

Kreuger, E., Sipos, B., Zacchi, G., Svensson, S.-E., Björnsson, L., 2011. Bioconversion of industrial hemp to ethanol and methane: the benefits of steam pretreatment and co-production. Bioresour. Technol. 102 (3), 3457–3465.

Kuglarz, M., Alvarado-Morales, M., Karakashev, D., Angelidaki, I., 2016. Integrated production of cellulosic bioethanol and succinic acid from industrial hemp in a biorefinery concept. Bioresour. Technol. 200, 639–647.

Kuglarz, M., Gunnarsson, I.B., Svensson, S.-E., Prade, T., Johansson, E., Angelidaki, I., 2014. Ethanol production from industrial hemp: effect of combined dilute acid/steam pretreatment and economic aspects. Bioresour. Technol. 163, 236–243.

Kyzas, G.Z., Terzopoulou, Z., Nikolaidis, V., Alexopoulou, E., Bikiaris, D.N., 2015. Low-cost hemp biomaterials for nickel ions removal from aqueous solutions. J. Mol. Liq. 209, 209–218.

Langholtz, M., Stokes, B., Eaton, L. 2016. 2016 Billion-ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, vol. 1: Economic availability of feedstock.

Lau, M.W., Dale, B.E., 2009. Cellulosic ethanol production from AFEX-treated corn stover using Saccharomyces cerevisiae 424A(LNH-ST). Proc. Natl. Acad. Sci. 106 (5), 1368–1373.

Lee, C., 2014. Kenaf-University of Kentucky, vol. 2017. http://www.agmrc.org/media/cms/Kenaf_introduction_00D587863A05B.pdf. (Last accessed, April 21th, 2017).

Leizer, C., Ribnicky, D., Poulev, A., Dushenkov, S., Raskin, I., 2000. The composition of hemp seed oil and its potential as an important source of nutrition. J. Nutr. Funct. Med. Foods 2 (4), 35–53.

LeMahieu, P.J., Oplinger, E.S., Putnam, D.H., 1991. Kenaf, vol. 2017. http://corn.agronomy.wisc.edu/Crops/Kenaf.aspx. (Last accessed, April 21th, 2017).

Li, C., Knierim, B., Manisseri, C., Arora, R., Scheller, H.V., Auer, M., Vogel, K.P., Simmons, B.A., Singh, S., 2010. Comparison of dilute acid and ionic liquid pretreatment of switchgrass: biomass recalcitrance, delignification and enzymatic saccharification. Bioresour. Technol. 101 (13), 4900–4906.

Linger, P., Müssig, J., Fischer, H., Kobert, J., 2002. Industrial hemp (*Cannabis sativa* L.) growing on heavy metal contaminated soil: fibre quality and phytoremediation potential. Ind. Crops Prod. 16 (1), 33–42.

Lu, F., Ralph, J., 1997. Derivatization followed by reductive cleavage (DFRC method), a new method for lignin analysis: protocol for analysis of DFRC monomers. J. Agric. Food. Chem. 45 (7), 2590–2592.

Missouri, U.o., 2015. Missouri Sorghum Facts, vol. 2017. http://crops.missouri.edu/audit/sorghum.htm. (Last accessed, April 21th).

Mitchell, R., Vogel, K.P., Schmer, M., 2016. Switchgrass (Panicum virgatum) for Biofuel Production, vol. 2017. http://articles.extension.org/pages/26635/switchgrass-panicum-virgatum-for-biofuel-production. (Last accessed, July 28th).

Mosier, N., Wyman, C., Dale, B., Elander, R., Lee, Y.Y., Holtzapple, M., Ladisch, M., 2005. Features of promising technologies for pretreatment of lignocellulosic biomass. Bioresour. Technol. 96 (6), 673–686.

Ooi, B.G., Rambo, A.L., Hurtado, M.A., 2011. Overcoming the recalcitrance for the conversion of kenaf pulp to glucose via microwave-assisted pre-treatment processes. Int. J. Mol. Sci. 12 (3), 1451–1463.

Perrin, R., Vogel, K., Schmer, M., Mitchell, R., 2008. Farm-scale production cost of switchgrass for biomass. Bioenergy Res. 1 (1), 91–97.

Prado, R., Brandt, A., Erdocia, X., Hallet, J., Welton, T., Labidi, J., 2016. Lignin oxidation and depolymerisation in ionic liquids. Green Chem. 18 (3), 834–841.

Robbins, L., Snell, W., Halich, G., Maynard, L., Dillon, C., Spalding, D., 2013. Economic Considerations for Growing Industrial Hemp: Implications for Kentucky's Farmers and Agricultural Economy Department of Agricultural Economics (AEC). University of Kentucky.

Ruan, Q., Qi, J., Hu, K., Cao, X., Lin, G., Wang, D., 2012. Bioconversion of fuel ethanol from kenaf stalk. J. Fujian Agric. For. Univ. (Natural Science Edition) 41 (1), 78–82.

Saba, N., Jawaid, M., Hakeem, K., Paridah, M., Khalina, A., Alothman, O., 2015. Potential of bioenergy production from industrial kenaf (Hibiscus cannabinus L.) based on Malaysian perspective. Renew. Sustain. Energy Rev. 42, 446–459.

Sassoni, E., Manzi, S., Motori, A., Montecchi, M., Canti, M., 2014. Novel sustainable hemp-based composites for application in the building industry: physical, thermal and mechanical characterization. Energy Build. 77, 219–226.

Selig, M., Weiss, N., Ji, Y., 2008. Enzymatic Saccharification of Lignocellulosic Biomass: Laboratory Analytical Procedure (LAP). Issue Date, 3/21/2008 National Renewable Energy Laboratory.

Shi, J., Qing, Q., Zhang, T., Wyman, C.E., Lloyd, T.A., 2011a. Biofuels from cellulosic biomass via aqueous processing. Fundam. Mater. Energy Environ. Sustain. 336–349.

Shi, J., Ebrik, M.A., Wyman, C.E., 2011b. Sugar yields from dilute sulfuric acid and sulfur dioxide pretreatments and subsequent enzymatic hydrolysis of switchgrass. Bioresour. Technol. 102 (19), 8930–8938.

Sipos, B., Kreuger, E., Svensson, S.-E., Reczey, K., Björnsson, L., Zacchi, G., 2010. Steam pretreatment of dry and ensiled industrial hemp for ethanol production. Biomass Bioenergy 34 (12), 1721–1731.

Sluiter, A., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J., Templeton, D., Crocker, D., 2008. Determination of structural carbohydrates and lignin in biomass. Lab. Anal. Proced. 1617, 1–16.

Sun, Y., Cheng, J., 2002. Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresour. Technol. 83 (1), 1–11.

Sun, W., Lipka, S.M., Swartz, C., Williams, D., Yang, F., 2016. Hemp-derived activated carbons for supercapacitors. Carbon 103, 181–192.

Tao, L., Aden, A., Elander, R.T., Pallapolu, V.R., Lee, Y.Y., Garlock, R.J., Balan, V., Dale, B.E., Kim, Y., Mosier, N.S., Ladisch, M.R., Falls, M., Holtzapple, M.T., Sierra, R., Shi, J., Ebrik, M.A., Redmond, T., Yang, B., Wyman, C.E., Hames, B., Thomas, S., Warner, R.E., 2011. Process and technoeconomic analysis of leading pretreatment technologies for lignocellulosic ethanol production using switchgrass. Bioresour. Technol. 102 (24), 11105–11114.

Templeton, D.W., Scarlata, C.J., Sluiter, J.B., Wolfrum, E.J., 2010. Compositional analysis of lignocellulosic feedstocks. 2. Method uncertainties. J. Agric. Food. Chem. 58 (16), 9054–9062.

USDA. 2016. Crop Production 2015 Summary, vol. 2017. https://www.ers.usda.gov/webdocs/publications/ages001e/15867_ages001e_1_.pdf. (Last accessed, April 21th, 2017).

USDA. 2000. Industrial Hemp in the United States: Status and Market Potential, vol. 2017. https://www.usda.gov/nass/PUBS/TODAYRPT/cropan16.pdf. (Last accessed, April 21th, 2017).

Wyman, C.E., Balan, V., Dale, B.E., Elander, R.T., Falls, M., Hames, B., Holtzapple, M.T., Ladisch, M.R., Lee, Y.Y., Mosier, N., Pallapolu, V.R., Shi, J., Thomas, S.R., Warner, R.E., 2011. Comparative data on effects of leading pretreatments and enzyme loadings and formulations on sugar yields from different switchgrass sources. Bioresour. Technol. 102 (24), 11052–11062.

Xu, J., Cheng, J.J., Sharma-Shivappa, R.R., Burns, J.C., 2010. Sodium hydroxide pretreatment of switchgrass for ethanol production. Energy Fuels 24 (3), 2113–2119.

Yang, B., Wyman, C.E., 2008. Pretreatment: the key to unlocking low-cost cellulosic ethanol. Biofuels, Bioprod. Biorefin. 2 (1), 26–40.

Yoo, C.G., Pu, Y., Li, M., Ragauskas, A.J., 2016. Elucidating Structural characteristics of biomass using solution-State 2 D NMR with a mixture of deuterated dimethylsulfoxide and hexamethylphosphoramide. ChemSusChem 9 (10), 1090–1095.