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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).

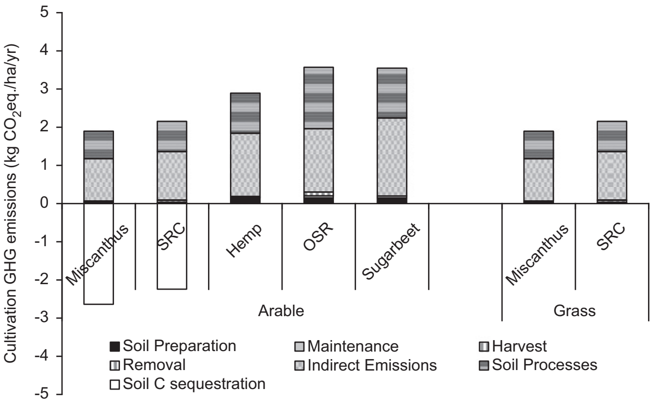

Fig. 1. Total GHG emissions arising from the cultivation of one hectare of the. different energy crops, including carbon sequestration, for mid-yield scenarios.

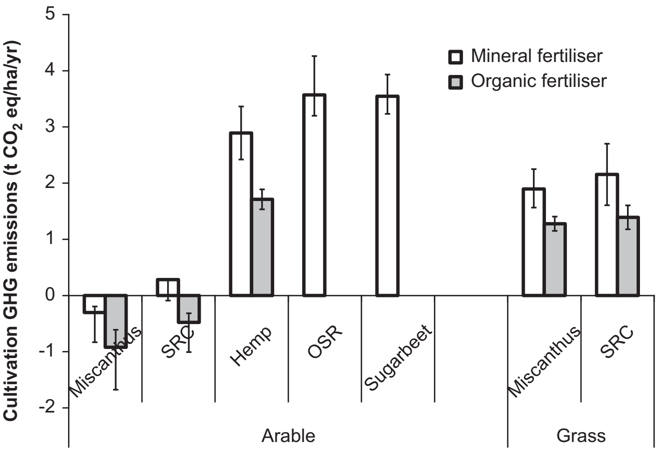

Fig. 2. Variation in net cultivation GHG emissions arising across the range of. yield estimates for each crop (error bars), and depending on either mineral or organic fertilizer application for Miscanthus, SRC and hemp.

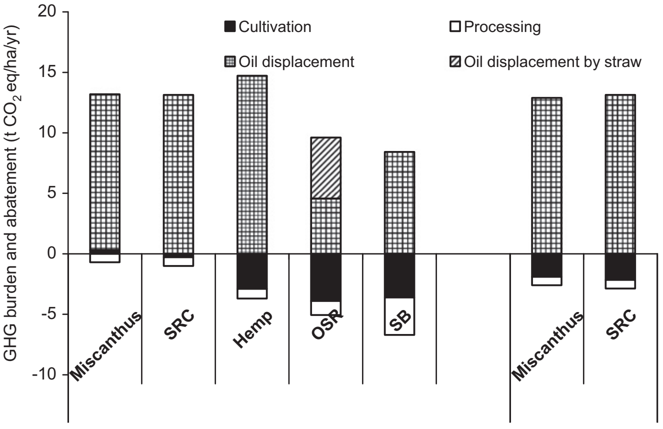

Fig. 3. Breakdown of GHG avoidance achieved by different energy crops, based on mid yield estimates.

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.

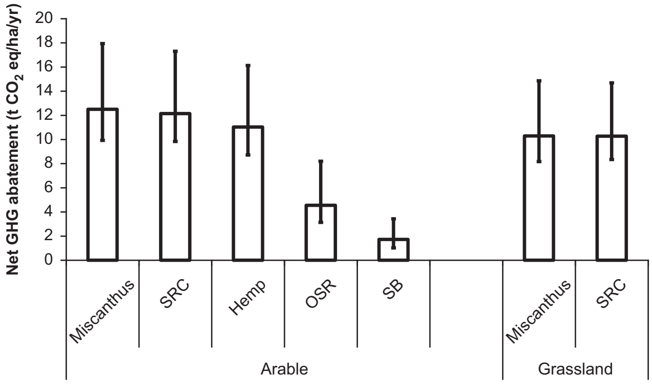

Fig. 4. Variation in net GHG avoidance across the range of yield estimates for. each crop (error bars).

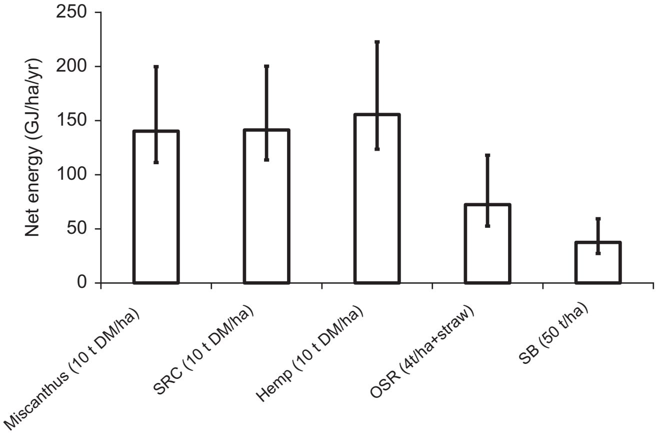

Fig. 5. Useful energy balance of fuel chains for the different crops.

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

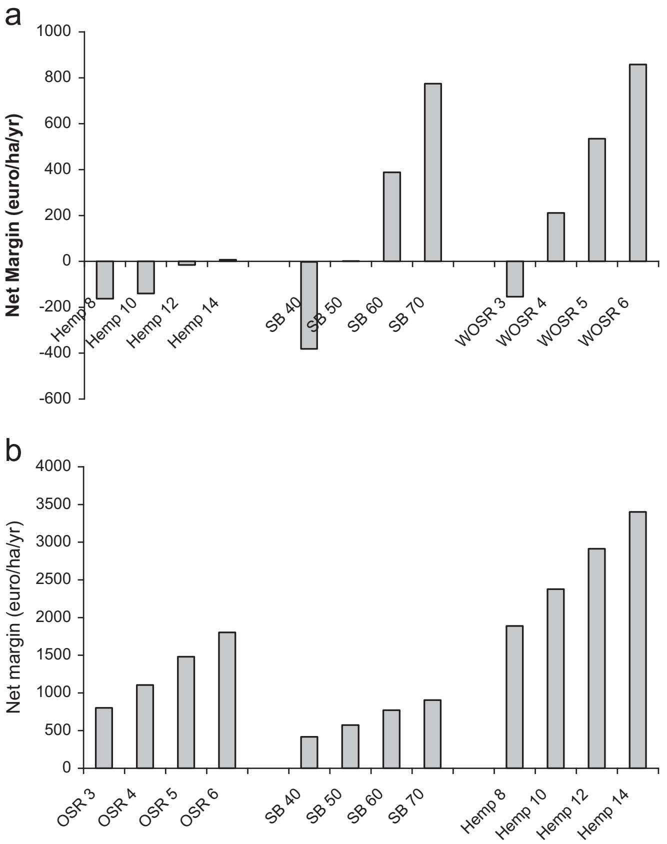

Fig. 6. Net margins of break crops. (a) current prices. Margins for hemp. assume a current price of €80/DM t. Net margins for sugar beet and winter oilseed rape are an average of three years 2009, 2010 and 2011. (b) Converting net energy into oil prices @ €0.54/L oil.

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).

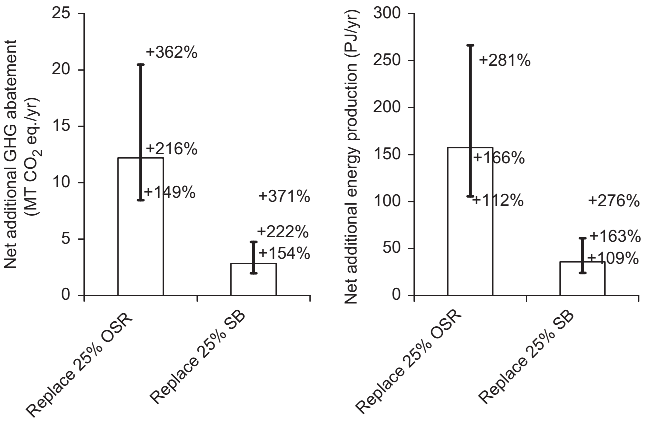

Fig. 7. The net additional GHG avoidance and energy production achievable. by replacing 25% of OSR and 25% of sugar beet grown in the EU with hemp used to substitute heating oil, based on mid yield (columns) and yield ranges (error bars) for hemp.

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.

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