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An assessment of the energy inputs and greenhouse gas emissions in sugar beet (*Beta vulgaris*) production in the UK

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Abstract

Reducing the energy derived from fossil fuels within agricultural systems has important implications for decreasing atmospheric emissions of greenhouse gases, thus assisting the arrest of global warming. The identification of crop production methods that maximise energy efficiency and minimise greenhouse gas emissions is vital. Sugar beet is grown in a variety of locations and under a variety of agronomic conditions within the UK. This study identified thirteen production scenarios, representative of over 90% of the UK beet crop, which included five soil types, nine fertiliser regimes and nine crop protection strategies. The fossil energy input, the overall energy efficiency and the global warming potential (GWP) of each production scenario was assessed. This study did not consider the processing of the beet to extract sugar.

The overall energy input of the UK beet crop ranges between 15.72 and 25.94 GJ/ha. It produces between 7.3 and 15.0 times as much energy in dry matter at the sugar factory gate as consumed in its production, with an average ratio of 9.7. It has an average GWP of 0.024 eq. t CO_2 per tonne of clean beet harvested, equivalent to 0.0062 eq. t CO_2 per GJ output. The energy input into each scenario was dictated largely by the energy associated with crop nutrition. The smallest energy inputs per hectare were to crops grown under organic

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conditions or conventional crops grown on fertile soils (clay loam, silt or peat) or sand soil with broiler manure applied. Those crops with the greatest energy input were grown on sand soil that was irrigated and had mineral fertiliser applied. Although the organic scenario grown on sandy loam soil had one of the smallest energy inputs per hectare, the low yield meant that the energy input was similar per tonne of beet harvested to the conventional crops grown on sandy loam soil. The extra distance travelled by organic beet from the farm to the factory increased the energy input per tonne above that of the conventional scenarios. The GWP was smallest for the conventional crops on the fertile peat and silt soils and greatest on the irrigated sand soils and the sandy loam soils. The organic scenario had a similar GWP to the conventional scenarios on sandy loam to the farm gate, although the greater diesel requirement for transport increased the GWP overall. The GWP per GJ of output for sugar beet in England is similar to published values for wheat.

Keywords: Sugar beet; Energy efficiency; Global warming; Sustainable agriculture

1. Introduction

Burning fossil fuels results in the emission of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) that act as barriers to thermal radiation and prevent it from leaving the Earth's atmosphere, the so-called 'greenhouse effect' (IPCC, 1997). As a consequence, the global mean temperature has increased during the past 100 years and raised concerns over global warming and uncertainty over future impacts on the climate (Pimentel et al., 1996). A reduction in greenhouse gas emissions by minimising the quantity of fossil fuels burnt is therefore essential to arrest global warming. Although the increased use of agricultural inputs in modern farming has resulted in an increase in the energy inputs for fertiliser and crop protection chemicals, higher yields have increased the energy output per unit area and per unit of input (Pimentel et al., 1973). The current policy within agriculture seeks to develop crop production systems that minimise fossil energy input for a high level of output (Dalgaard et al., 2000). In 2002, 169,043 ha were devoted to sugar beet (*Beta vulgaris*) production in the UK (DEFRA, Agricultural Statistics, 2003), an important component of the UK arable sector. The impact of the UK sugar beet crop on the environment and, for the purpose of this study, the atmosphere, requires scrutiny. This study uses two methods to assess the environmental impact of the UK sugar beet crop. Firstly, energy balance techniques described in Hülsbergen and Kalk (2001) were used to examine the quantity of energy input relative to energy output for the crop as a whole. Because the crop is grown in many different ways, we have represented this by 13 production scenarios, estimated to include 90% of current production methods in the UK. Secondly, the overall global warming potential (GWP), an index that describes the relative warming of a unit mass of a greenhouse gas in comparison to the same mass of carbon dioxide (Maunder, 1992), was calculated for each scenario. The results are discussed with respect to optimising the energy efficiency of the UK sugar beet crop and minimising greenhouse gas emissions.

2. Methods

2.1. Description of scenarios

The proportion of the areas grown under each crop production regime within the UK and their expected average yields are given in Table 1. Scenarios I–XII are under conventional production, scenario XIII is organic. Scenarios I–VI are grown on sand, VII–XIII on sandy loam, IX on clay loam, X on silt and XI and XII on peat. The nutrition, cultivation and pesticide regimes for each scenario are summarised in Tables 1–3, respectively. Scenarios I–IV are irrigated and scenario VI is under minimum tillage. To control wind erosion, Scenarios III and XI have a spring barley cover crop drilled at the end of February and an application of the herbicide Fusilade® (fluazifop-*p*-butyl) in late April or early May to remove it.

2.2. Energy balance

The energy balance was based on the technique described in Hülsbergen and Kalk (2001) and considered the input of fossil energy into the system. The input from manual labour and from the sun was not included. Beet tops were assumed to be re-invested within the field system and thus excluded from the overall output for each scenario. The energy requirements for each production scenario (expressed as megajoules per hectare (MJ/ha)) were divided into four sections: crop protection, nutrition, cultivations and culture. The sub-sections are further divided by:

i. energy for the manufacture of crop protection chemicals and fertilisers (including packaging and transport to the farm);
ii. energy required for carrying out of field operations. Each operation was assigned a value based on the type and working width of machine and in the case of tillage operations, the operating depth and soil type;
iii. indirect energy (the energy required for the manufacture of machinery and its maintenance). The operating lifetimes and depreciation periods of the machines were as described by Hülsbergen and Kalk (2001);
iv. the energy costs for transport of the beet from the farm to the sugar factory.

The sub-divisions were combined to give an overall estimate of total energy requirement per hectare, and to give an estimate of energy input per tonne of clean beet harvested. The energy content of the beet delivered to the factory gate and the output/input energy ratio per hectare were calculated.

2.2.1. Crop protection

The energy required to manufacture the majority of the agro-chemicals applied were not available directly, although Green (1987) provides values for 24 herbicides, 4 fungicides and 11 insecticides. The majority of energy balance studies to date use the mean values for each pesticide type. In this study, the values provided by Green (1987) for specific pesticides were assigned to their chemical group (Table 4). Where

Table 1
The area grown, soil type, quantity of nutrients applied and adjusted yield of each sugar beet production scenario

Scenario	% Area	Soil type	Yield (t/ha)[a]	Lime (t/ha)	Organic N (t/ha)	Inorganic N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	MgO (kg/ha)	Na (kg/ha)	$MnSO_3$ (kg/ha)	B spray (kg/ha)
I	2	Sand	50	2	30 FYM	80	–	–	–	–	–	–
II	2	Sand	50	2	–	120	50	100	85	150	10	7
III	1	Sand	50	2	–	120	50	100	85	150	10	7
IV	2	Sand	55	2	10 broiler	40	–	–	–	–	–	–
V	10	Sand	45	2	–	120	50	100	85	150	–	7
VI	2	Sand	45	2	–	120	50	100	85	150	–	7
VII	12	Sandy loam	50	2	30 FYM	80	–	–	–	–	–	–
VIII	24	Sandy loam	50	2	–	120	50	100	85	150	–	–
IX	21	Clay loam	50	–	–	120	50	50	–	150	–	–
X	18	Silt	60	–	–	120	50	50	–	–	–	–
XI	2	Peat	60	–	–	30	50	50	85	–	20	10
XII	4	Peat	60	–	–	30	50	50	85	–	20	10
XIII (organic)	0.2	Sandy loam	34	2	–	–	–	100	–	–	–	–

[a] Refers to clean weight adjusted to 16% sugar concentration.

Table 2
The timing of cultivations, mechanical weed control and irrigation for each sugar beet production scenario

Operation	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
Stubble cultivation	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep
	–	–	–	–	–	–	–	–	–	–	–	–	30 Sep
Subsoil (35 cm)	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	15 Sep	–	–	–	–	15 Sep
Plough and press (25 cm)	15 Feb	15 Feb	15 Feb	15 Feb	15 Feb	–	15 Nov	15 Nov	01 Nov	01 Nov	15 Dec	15 Dec	15 Nov
Tine cultivate (10 cm)	–	–	–	–	–	13 Mar	–	–	–	–	–	–	13 Mar
Seedbed cultivation (5 cm)	–	–	20 Feb	20 Feb	15 Feb	–	15 Mar	15 Mar	01 Apr	01 Apr	24 Feb	01 Apr	01 Apr
	–	–	–	–	–	–	–	–	01 Apr	01 Apr	–	–	15 Apr
Tractor hoe	30 May	30 May	–	30 May	30 May	30 May	30 May	30 May	30 May	30 May	–	–	01 May
	–	–	–	–	–	–	–	–	–	–	–	–	10 May
	–	–	–	–	–	–	–	–	–	–	–	–	25 May
	–	–	–	–	–	–	–	–	–	–	–	–	05 Jun
Cross harrow	–	–	–	–	–	–	–	–	–	–	–	–	20 May
	–	–	–	–	–	–	–	–	–	–	–	–	05 Jun
Mow	–	–	–	–	–	–	–	–	–	–	–	–	02 Aug
Irrigate (25 mm/ha)	15 Jul	15 Jul	15 Jul	15 Jul	–	–	–	–	–	–	–	–	–
	30 Jul	30 Jul	30 Jul	30 Jul	–	–	–	–	–	–	–	–	–

Table 3
The pesticide treatments and application dates for each sugar beet production scenario

Pesticide	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
Betanal Flo (2.5 l/ha)	–	–	–	–	–	–	–	–	–	–	14 Apr	–	–
Betanal Tandem (3 l/ha)	–	–	–	–	–	–	–	–	–	–	03 Jun	04 Jun	–
Dow shield (0.5 l/ha)	–	–	–	–	–	–	–	–	–	22 May	–	–	–
Fusilade (0.5 l/ha)	–	–	24 Apr	–	–	–	–	–	–	–	06 May	–	–
Gaucho (0.099 kg/ha)	–	–	–	–	–	–	17 Mar	17 Mar	17 Mar	17 Mar	17 Mar	17 Mar	–
PDQ (3 l/ha)	–	–	–	–	–	–	–	–	–	–	–	03 Apr	–
Punch C (0.625 l/ha)	06 Aug	06 Aug	06 Aug	06 Aug	06 Aug	06 Aug	06 Aug	06 Aug	06 Aug	06 Aug	06 Aug	06 Aug	–
Pyramin DF	–	–	15 Mar[1]	–	–	–	18 Mar[2]	18 Mar[2]	10 Apr[3]	10 Apr[3]	–	–	–
Sting Eco (3 l/ha)	17 Mar	17 Mar	01 Feb	17 Mar	17 Mar	17 Mar	01 Nov	01 Nov	–	–	–	–	–
Temik (10 kg/ha)	15 Mar	15 Mar	15 Mar	15 Mar	15 Mar	15 Mar	–	–	–	–	–	–	–
Thiovit (10 kg/ha)	–	–	–	–	–	–	–	–	–	–	–	–	06 Aug
1: GWG[2] + BF[1]	–	–	–	–	–	–	–	09 Apr	23 Apr	23 Apr	–	14 Apr	–
2: BP + VF + oil	–	–	–	21 Apr	21 Apr	21 Apr	23 Apr	23 Apr	08 May	08 May	–	–	–
3: BF[2] + Vz	06 Apr	06 Apr	06 Apr	06 Apr	06 Apr	06 Apr	09 Apr	–	–	–	–	–	–
4: BF[1] + Vz + Db + oil + Cl	–	–	–	–	–	–	–	–	–	–	25 May	25 May	–
5: BF[2] + GWG[2] + oil + Cl	–	–	–	–	–	–	–	–	–	–	24 Apr	24 Apr	–
6: BT + GWG[1] + oil	–	–	–	05 May	05 May	–	–	–	–	–	–	–	–
7: BP + Db + VF + oil + Cl	21 Apr	21 Apr	21 Apr	–	–	05 May	–	–	–	–	03 May	04 May	–
8: BT + GWG[1] + oil + Cl	05 May	05 May	05 May	–	–	–	–	–	–	–	–	–	–

Numbers 1–8 refer to mixes.
BF: Betanal Flo [1]1.5 l/ha [2]1.7 l/ha; BP: Betanal Progress 0.75 l/ha; BT: Betanal Tandem 3 l/ha; Cl: clopyralid 0.5l/ha; Db: Debut 30.0 g/ha; GWG: Goltix WG [1]1 kg/ha [2]1.25 kg/ha [3]1.7 kg/ha; oil, 1.0 l/ha; Pyramin DF [1]1.7 kg/ha [2]2.5 kg/ha [3]3.3 kg/ha; VF: Venzar Flo 0.4 l/ha; Vz: Venzar 0.4 l/ha.

Table 4
Energy (MJ/kg) required for the manufacture of pesticides (based on values from Green, 1987)

Product	Group	Energy (MJ/kg)
Aldicarb	Carbamate	207
Carbendazim	Benzidimazole	397
Chloridazon	Pyridazinone	264[a]
Clopyralid	Picolinic	264[a]
Desmedipham	Carbamate	207
Diquat	Bipyridylium	400
Ethofumesate	Benzofuran	264[a]
Flusilazole	Triazole	168[b]
Fluazifop-*p*-butyl	Fop	518
Glyphosate	Phosphonic	454
Hymexazol	Isoxazole	168[b]
Imidacloprid	Nitroimidazolidinimime	214[c]
Lenacil	Uracil	264[a]
Metamitron	Triazinone	196
Paraquat	Bipyridylium	460
Phenmedipham	Carbamate	207
Sulphur		4.6
Thiram	Thio-carbamate	207
Triflusulfuron	Sulfonyl urea	365

Mineral oil was assigned a value of 38.7 MJ/l (Dawson, 1978).
[a] Mean value of 24 herbicides.
[b] Mean value of four fungicides.
[c] Mean value of 11 insecticides.

there was more than one value for a group, the mean was taken. Those pesticides that did not belong to one of the chemical groups in Green's study were assigned the mean value of each pesticide type (herbicide, fungicide or insecticide). An additional 23 MJ/kg was added to each value to account for storage and transport to the farm (Hülsbergen and Kalk, 2001). The energy requirement to manufacture each pesticide application is given in Table 5.

Spray application of agro-chemicals was estimated to require 1.7 l/ha of diesel with an additional 29 MJ/ha of indirect energy (Hülsbergen and Kalk, 2001). Diesel consumption releases 39.6 MJ/l (Reinhardt, 1993; cited Hülsbergen and Kalk, 2001).

2.2.2. Cultivations

The energy consumed while ploughing and sub-soiling on various soil types was derived from the regression equations described in Kalk and Hülsbergen (1999).

For those scenarios that used a press behind the plough, 20% was added to the calculated energy requirement (Table 6). For all other cultivations (Table 6), it was assumed that the implement was pulled by a 100-kW turbo-cooled diesel tractor at 10 km/h. The energy required for each operation was calculated using the method described by Hunt (1995). Indirect energy values were assumed as 152 MJ/ha for stubble cultivation and 143 MJ/ha for ploughing (Hülsbergen and Kalk, 2001) and all other tillage operations.

Table 5
The energy (MJ) required for each pesticide application

Pesticide	Rate	Energy (MJ)[a]
Agrichem Flowable Thiram (thiram)	0.0083 kg/ha	2
Betanal Tandem (ethofumesate/phenmedipham)	3.0 l/ha	141
Dow Shield (clopyralid)	0.5 l/ha	29
Fusilade (fluazifop-*p*-buty)	0.5 l/ha + 1 l/ha oil	68 + 39
Gaucho (imidacloprid 70% w/w)	0.099 kg/ha	16
PDQ (diquat/paraquat)	3.0 l/ha	275
Punch C (carbendazim/flusilazole)	0.625 l/ha	63
Pyramin DF (chloridazon 65% w/w)	1.7 kg/ha	317
Pyramin DF (chloridazon 65% w/w)	2.5 kg/ha	466
Pyramin DF (chloridazon 65% w/w)	3.3 kg/ha	616
Sting Eco (glyphosate)	3.0 l/ha	172
Tachigaren (hymexazol)	0.015 kg/ha	3
Temik (aldicarb 10% w/w)	10.0 kg/ha	230
Thiovit (sulphur 80% w/w)	10.0 kg/ha	37
Mix 1	See Table 3	293
Mix 2	See Table 3	145
Mix 3	See Table 3	113
Mix 4	See Table 3	140
Mix 5	See Table 3	140
Mix 6	See Table 3	333
Mix 7	See Table 3	174
Mix 8	See Table 3	362
Mix 9	See Table 3	328

[a] Including 23 MJ/kg active ingredient for storage and transport (except sulphur).

2.2.3. Nutrition

The chemical composition of fertiliser products are given in Table 7 in addition to the energy values for their manufacture. The most modern ammonium nitrate fertiliser manufacturing factories have an accumulated production cost of 30.5 MJ/kg N (Jenssen and Kongshaug, 2003). However, the present day 'average Europe' value incorporates the production costs of older plants to give an accumulated production cost of 38.7 MJ/kg N (Jenssen and Kongshaug, 2003): this is the value assumed here. An additional 1.3 MJ/kg accounts for packaging and transport (Kaltschmidt and Reinhardt, 1997). Farmyard and broiler manures were assumed to be by-products whose production incurred no energy cost. Data for calcined magnesite, manganese sulphate, boron spray and agricultural salt were not available so an estimate was based on the extraction of raw material (Jenssen and Kongshaug, 2003), packaging and transport (Kaltschmidt and Reinhardt, 1997) and processing.

The diesel consumption (l/ha) for the application of fertiliser products were derived from regression equations described in Kalk and Hülsbergen (1999). For the simultaneous application of fertiliser products the weights were totalled for use in the regression equation, with an additional 28 MJ/ha indirect energy (Hülsbergen and Kalk, 2001). The application of 30 t/ha farmyard manure required 16.6 l/ha and 813 MJ/ha indirect energy (Hülsbergen and Kalk, 2001). The loading and transport of livestock manures were assigned energy values of 0.5 l/t (Daalgard, 2001) and

Table 6
Energy input for cultivations (MJ/ha) in relation to soil type

Operation	Energy (MJ/ha)
Plough (23 cm)	624–1160[a]
Plough and press	749–1392[a]
Stubble cultivation	166
Spring cultivations (light soils)	138
Spring cultivations (heavy soils)	330[b]
Subsoil (35 cm)	1061–1560[a]
Rotary hoe	95
Mow	139

The plough and sub-soil values are derived from regression equations from Kalk and Hülsbergen (1999) with the press assumed as 20% of the plough value. All other values are derived from Hunt (1995).

[a] The range of values assumed for the ploughing of sand, peat, sandy loam, clay loam and silt soils or the subsoiling of sand and sandy loam soils.

[b] It is assumed that two passes of a field cultivator are required to create a seedbed on heavy soil.

Table 7
Chemical composition of fertiliser products and energy values for their manufacture (including packaging and transport)

Product	Composition	Energy for manufacture
Ammonium nitrate (average Europe)	34.5%N	38.7[a] MJ/kg N (Jenssen and Kongshaug, 2003)
Triple superphosphate	48%P_2O_5 (P_2O_5: 43.6%P)	12.0 MJ/kg P (Daalgard, 2001)
Muriate of potash	60%K_2O (K_2O: 83%K)	7.0 MJ/kg K (Daalgard, 2001)
Sylvinite	24%K_2O (K_2O: 83%K)	7.0 MJ/kg K (Daalgard, 2001)
Lime		0.03[a] MJ/kg (Refsgaard et al., 1998)
Calcined magnesite	80%MgO	8.75[b] MJ/kg MgO
Boron spray		5.0[c] MJ/kg product
Salt		2.5[c] MJ/kg product
Manganese sulphate		2.5[c] MJ/kg product

[a] Excludes packaging and transport for which an additional 1.3 MJ/kg is added (Kaltschmidt and Reinhardt, 1997).

[b] Based on mineral extraction values of 0.8 MJ/kg (Jenssen and Kongshaug, 2003), transport of 1.3 MJ/kg (Kaltschmidt and Reinhardt, 1997) plus an additional estimate for the calcining of raw magnesite in a furnace.

[c] Based on mineral extraction values of 0.8 MJ/kg (Jenssen and Kongshaug, 2003), transport of 1.3 MJ/kg (Kaltschmidt and Reinhardt, 1997) plus an additional estimate for product processing.

0.2 l/t/km (Daalgard, 2001), respectively. There are no data for manure transport distances to beet fields, but we have assumed an average of 10 km; in all probability this is an overestimate.

2.2.4. Crop culture and delivery

The energy values associated with the culture of the crop are given in Table 8. The indirect energy for the harvest of beet was 1074 MJ/ha (Hülsbergen and Kalk, 2001). The indirect energy values for drilling, irrigation and transport to the clamp were estimated at 75, 29 and 28 MJ/ha, respectively. Those for cleaning and loading were estimated at 100 MJ/ha.

Table 8
Energy values (MJ) or fuel consumption (litres of diesel) required for crop culture operations

	Energy value/fuel consumption
Beet seed	250.0 MJ/unit (Stephan, 1997)
Cover crop seed (spring barley)	5.5 MJ/kg (Kalk et al., 1995)
Drill	240.0 MJ/ha (Green, 1987)
Irrigation	52.0 MJ/mm/ha (Daalgard, 2001)
Harvest	47.0 l/ha (K. Jaggard *pers comm.*)
Transport to clamp (2 km)	0.2 l/t/km (Daalgard, 2001)
Clean and load	0.5 l/t (Daalgard, 2001)

The average distance for each tonne of beet from the farm to the factory was 46 km in 2002. We assumed the transport used a 38-t gross weight truck with an energy requirement of 0.016 l/t/km (Küsters, 1999). The return journey assumed the empty truck weighed 12 t and, for example, a 50-t/ha yield would require 2.1 loads/ha of empty journeys at 0.016 l/t/km. The average distance to transport organic beet was estimated as 144 km (K. Jaggard *pers comm.*).

2.2.5. Global warming potential

Atmospheric emissions from each source of fuel and their GWP, expressed as tonnes of CO_2 equivalent are given in Table 9. The proportion of each fuel source used in manufacture, field operations and indirect energy are given Table 10.

Table 9
Gaseous emissions (kg) from fuel sources and their global warming potential (GWP) (from Houghton, 1996)

Fuel source	CO_2	N_2O	CH_4
Electricity (kWh)	0.0612	0.882^{-6}	2.77^{-6}
Natural gas (kWh)	0.209	2.59^{-6}	22.0^{-6}
Diesel (l)	2.73	18.1^{-6}	173.0^{-6}
Fuel oil (l)	3.16	24.7^{-6}	57.7^{-6}
Naptha (l)	3.42	0	113.0^{-6}
GWP CO_2 equivalence factor	1	310	21

Table 10
Proportion of fuel source (%) for product manufacture, field operations and indirect energy (from Green, 1987)

Operation	Electricity[a]	Natural gas	Diesel	Fuel oil	Naptha
N fertiliser manufacture	5	95	0	0	0
PK fertiliser manufacture	0	0	0	100	0
Pesticide manufacture	40	22	0	5	33
Transport	0	0	100	0	0
Field operations	0	0	100	0	0
Irrigation	30	0	70	0	0
Indirect	70	0	30	0	0

[a] Assumes generated by fuel sources in the following proportions: coal 34%, oil 2%, natural gas 32%, nuclear and other renewable sources 32% (Eurostat, 1998).

3. Results

3.1. Crop protection

With the exception of the organic crop, most of the crop protection interventions involved the use of pesticides. The energy content of each application is listed in Table 5. Scenarios that used chloridazon, a herbicide especially useful on heavy soils but that requires large application rates, had large crop protection energy costs. Aldicarb, used for nematode and aphid control on sand soils, also represents a large energy consumption (aldicarb will not be used after 2004, but its role will tend to be taken by other nematicides applied at similar doses). The overall energy requirement for crop protection tended to be lowest in those crops grown on sand soils and was greatest on the more nutrient rich soils, especially the peat soils (Table 11) that require several herbicide applications to control the many weed flushes. The use of mechanical weed control within the organic system resulted in a greater energy cost than the conventional crops grown on the same soil that used herbicides.

3.2. Nutrition

The smallest energy requirement for crop nutrition were in the conventional scenarios on peat soil and the organic scenario on sandy loam (Table 11). The application of lime provides a suitable pH for several successive crops but in the rotation, it is often applied to beet, the most acid-sensitive of the common arable species. Similarly, in an organic rotation, sylvinite may be applied if it is necessary to maintain soil fertility but nutrients from this application will support several subsequent crops. Many peat, silt and clay loam soils contain sufficient potash such that only a maintenance dressing is required thus the energy input for this nutrient was small and lime was not required. Peat and silt soils usually contain sufficient sodium that none need

Table 11
The energy input (GJ/ha) for crop protection, nutrition, cultivation, crop culture and off farm transport for each sugar beet production scenario

Scenario	Crop protection	Nutrition	Cultivation	Crop culture	Off farm transport
I	1.8	10.7	2.6	8.2	2.1
II	1.8	10.8	2.6	8.2	2.2
III	2.3	10.8	2.7	8.8	2.2
IV	1.8	6.6	2.9	8.4	2.4
V	1.8	10.7	2.6	5.3	1.9
VI	1.8	10.7	1.6	5.3	1.9
VII	1.8	10.7	3.6	5.5	2.2
VIII	2.0	10.6	3.7	5.5	2.2
IX	2.2	6.7	2.6	5.5	2.2
X	2.3	5.7	2.6	5.9	2.6
XI	2.3	3.1	1.5	6.5	2.6
XII	2.6	3.1	1.5	5.9	2.6
XIII	2.0	3.5	3.9	5.0	4.5

be applied, while peat soils mineralize large quantities of nitrogen so that only a small application of this nutrient is necessary. The crops grown on clay loam and silt soil had energy inputs for nutrition of approximately 4000 and 5000 MJ/ha lower than that on sand or sandy loam soil with much of the difference attributed to differences in the need for nitrogen fertiliser. The manufacture of mineral fertiliser, not including lime and its transport, accounted for about 7400 MJ/ha when applied to crops grown on sand or sandy loam, with between 306 and 364 MJ/ha for field operations. If 30 t/ha of farmyard manure is applied, about 2400 and 600 MJ/ha are required for loading and transport, respectively, with 660 MJ/ha for application. Broiler manure was applied at one third of the rate of farmyard manure and the associated energy costs for its transport and application were also approximately one third.

3.3. Cultivation

The scenarios with the lowest energy requirement for cultivation had fewer deep tillage operations (ploughing and/or sub-soiling), or were on lighter soils (sand or peat) (Table 11). The scenarios on the clay loam and silt soils were not sub-soiled although ploughing alone incurred a greater energy cost than for the other soil types. The conventional scenarios on sandy loam and the organic scenario had large energy requirements for cultivation: both of the conventional scenarios were sub-soiled and ploughed while the organic scenario had an additional tine cultivation to control weeds prior to sowing. We have assumed that all of the sand and sandy loam soils were subsoiled at an energy requirement of 1060 and 1560 MJ/ha, respectively, although in reality, many of these soils are not subsoiled before every beet crop.

3.4. Crop culture

The energy used in crop culture is greatly increased by the use of irrigation, an additional 2.6 GJ/ha, while the growing and removal of a barley cover crop required 590 MJ/ha.

3.5. Total energy input per tonne of clean beet harvested

The total energy inputs per tonne of clean beet harvested are shown in Figs. 1 and 2. The higher yields and lower energy inputs into scenarios X–XII resulted in the least energy input per tonne of beet to the farm gate with values of 274, 223, and 216 MJ/t, respectively. Of the scenarios on sand soil, scenario IV required the least energy input (356 MJ/t) on account of a lower energy input for nutrition and a higher yield. Of the scenarios on sand that applied mineral fertiliser, the minimum tilled crop (scenario VI) required the least input per tonne (430 MJ/t) despite its lower yield on account of no irrigation and lower cultivation costs. Scenario III required the greatest energy input (492 MJ/t) owing to higher energy inputs for nutrition, crop protection and culture compared to scenarios I and II, despite yielding the same. Although the organic crop had a low energy input per unit area, the low yield

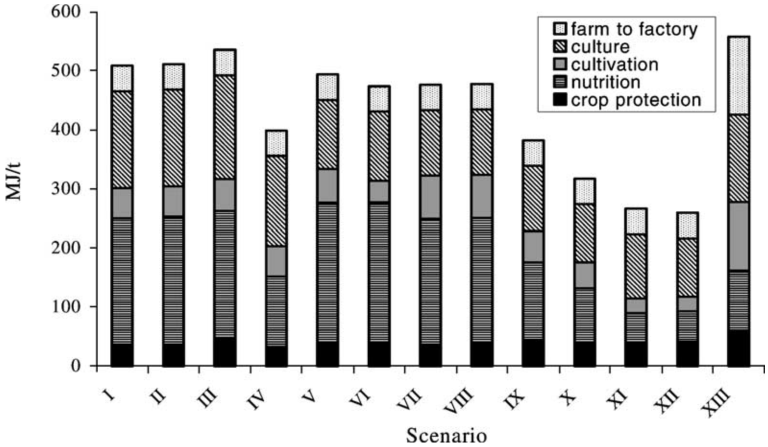

Fig. 1. Total energy input per adjusted tonne of clean beet harvested in each scenario, categorised by crop protection, nutrition, cultivation and crop culture.

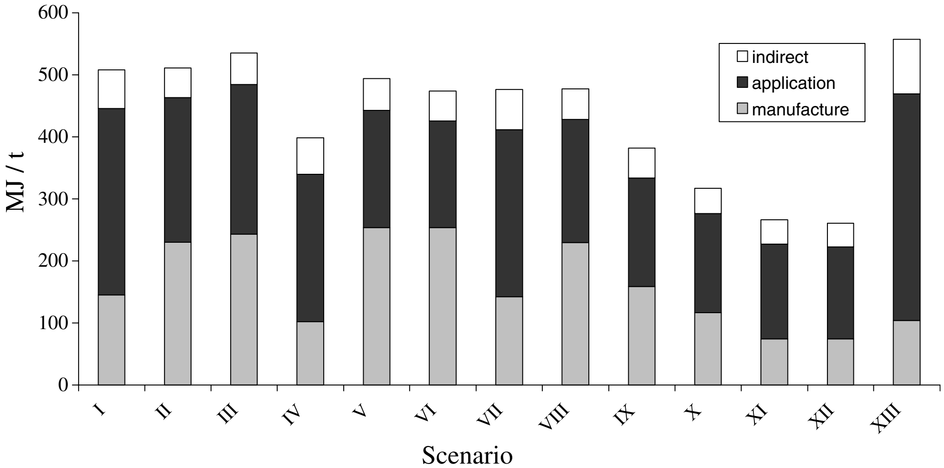

Fig. 2. Total energy input per adjusted tonne of clean beet harvested in each scenario, categorised by manufacture, application and indirect.

(34 t/ha) resulted in the energy input at the farm gate being 425 MJ/t, slightly less than the conventional scenarios on sandy loam that were 433 and 435 MJ/t. In the UK, there is one factory located in Newark that processes organic beet. Organic beet therefore has to be taken to this location irrespective of where it is grown within the UK, unlike conventional beet that will be processed in the factory nearest to where it is produced. The greater average distance to transport organic beet to the Newark factory compared to the conventional scenarios increased the energy requirement to 557 MJ/t, a value greater than any conventionally produced crops.

Table 12
The energy efficiency for each scenario described as the ratio between energy output (GJ/ha) and energy input (GJ/ha) and global warming potential (GWP)/ha expressed as equivalent tonnes of carbon dioxide

Scenario	Energy output (GJ/ha)	Energy input (GJ/ha)	Output/input ratio	GWP (eq. t CO_2)/ha	GWP (eq. t CO_2)/t clean beet	GWP (eq. t CO_2)/GJ output
I	195.0	25.41	7.67	1.5	0.03	0.00769
II	195.0	25.55	7.63	1.47	0.029	0.00754
III	195.0	26.76	7.29	1.54	0.031	0.00790
IV	214.5	21.92	9.78	1.26	0.023	0.00587
V	175.5	22.22	7.90	1.28	0.028	0.00729
VI	175.5	21.32	8.23	1.22	0.027	0.00695
VII	195.0	23.81	8.18	1.42	0.028	0.00728
VIII	195.0	23.88	8.16	1.38	0.028	0.00708
IX	195.0	19.10	10.21	1.09	0.022	0.00559
X	234.0	19.02	12.30	1.1	0.018	0.00470
XI	234.0	15.97	14.65	0.93	0.016	0.00397
XII	234.0	15.64	14.96	0.91	0.015	0.00389
XIII	132.6	18.95	7.00	1.16	0.034	0.00875

3.6. Energy input and output

One tonne of dry beet contains 16.9 GJ of energy (Austin et al., 1978) while the harvested beet product contains 23% dry matter. The energy output for each scenario was calculated thus:

Energy output/ha = 16.9 ∗ 0.23 ∗ yield of clean beet/ha.

The energy output/input ratio was calculated by dividing the total energy output by the energy input.

The most energy efficient scenarios, those with a high output/input ratio, are the crops grown on peat or silt and to a lesser extent, clay loam soils (Table 12). The conventional sandy loam scenarios were generally more efficient than the crops grown on sand, with the exception of the minimum tilled scenario on sand and the scenario to which broiler manure was applied. The organic crop was the least energy efficient production scenario. The average output/input ratio for the whole of the UK, based on the proportion of crops grown under each scenario, was 9.7.

3.7. Global warming potential

The GWP (expressed as equivalent tonnes of carbon dioxide per hectare) for each scenario is summarised in Fig. 3 and the GWP per tonne of beet is given in Table 12. The GWP per hectare was lowest in the scenarios on peat soils, then silt and clay loam, mainly as a result of a low GWP associated with small inputs of fertiliser. The high yielding peat and silt scenarios had the lowest GWP per tonne of clean beet. The scenarios on sand that used farmyard manure or mineral fertiliser in addition to irrigation had the largest GWP per hectare. The crops that had broiler manure applied or used minimum tillage had the lowest GWP value of those crops grown

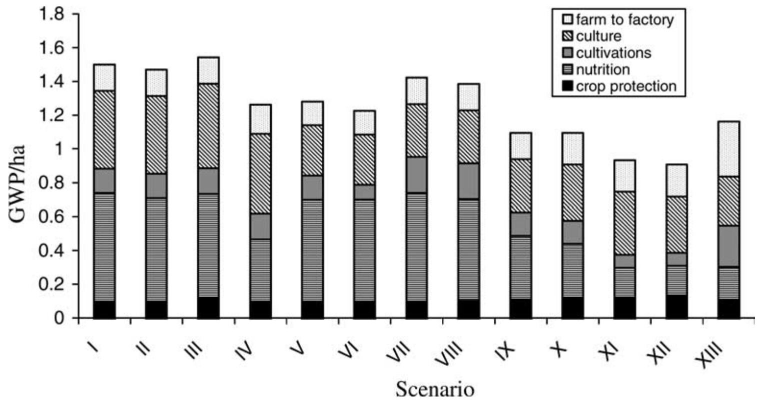

Fig. 3. Global warming potential (GWP) expressed as tonnes CO_2 equivalent per hectare of beet grown.

on sand. The GWP of the organic scenario was low on farm but was increased greatly as a result of the greater distance to transport the organic beet to the factory. The low yield resulted in the greatest GWP per tonne of clean beet. The average GWP per tonne of clean beet for the whole of the UK based on the proportion of crops grown under each scenario is 0.024 eq. t CO_2/t.

4. Discussion

The overall energy input for beet production in the UK ranged between 15.72 and 25.94 GJ/ha, similar to the estimate of Hülsbergen and Kalk (2001) who found that sugar beet production in Germany required between 14.2 and 36.9 GJ/ha with a mean of 29.49 GJ/ha. Hülsbergen and Kalk (2001) assigned a mean energy value of 6.96 GJ/ha for the production of livestock manure which was not included in this study.

The energy input for sugar beet production was found to be largely influenced by crop nutrition that is, in turn, dictated by the soil type on which the beet crop is grown. The energy required for the manufacture of fertiliser, in particular nitrogen, or the application of large volumes of livestock manure comprised a significant portion of the energy input to crops grown on the less fertile soils. On the nutrient rich soils low nitrogen and potassium input without the need for lime or salt, in addition to a low energy requirement for seedbed cultivation, meant that despite the many post emergence herbicide treatments, the overall energy input was low while yields were high. Where livestock manure is used, much of the crop's nutrient requirements are supplied. This reduces the energy input slightly but more importantly, recycles nutrients and improves the overall sustainability of the system. We assumed that the manure was transported 10 km and minimising this distance is an important consideration. It is also worth noting that the industrial processes to manufacture fertiliser are becoming more energy efficient and as a consequence, the energy input for the manufacture of ammonium nitrate and phosphorous fertiliser will decrease in the future (Jenssen and Kongshaug, 2003). Mineral fertiliser therefore, will probably become a more energy efficient method to feed crops compared to farmyard manure unless the manure is produced near to the field where it is applied.

The use of minimum tillage on sand soil required one of the lowest inputs with respect to crop cultivation, thus minimum tillage offers potential for a reduction in energy input to beet production. A comparison of integrated and conventional production by Bailey et al. (2003) concluded the use of minimum tillage in integrated systems to be one of the key differences between the energy inputs of the two. For the UK sugar beet crop, minimum tillage does reduce the energy input but does not have the greatest influence. Bailey et al. (2003) also found however, that crop output in minimum tilled crops was reduced in certain cases as a result of increased weed populations that reduced crop yield. The viability of using such techniques must be considered on a farm specific basis. It should also be noted that many whole-rotation improvements, such as subsoiling and liming, have been included as part of the costs of the beet crop in the current study. In reality they should be associated with other crops in the rotation also.

Other key factors included the use of irrigation on sand and deep cultivations on heavier soils, such as silt and clay. Crop protection did not have as great an impact, mainly as a result of the small quantities of active ingredients required and the small quantity of energy associated with the spraying of chemicals.

It should be noted that the yield of beet in the current study is grown to optimise sugar yield and not for root yield and thus is expressed as washed and adjusted to a 16% sugar content standard. Hülsbergen and Kalk (2001) refer to the use of a 'grain equivalent' as a means of benchmarking crops based on their nutritional content as opposed to solely their calorific content in order to allow comparisons between, for example, crops grown for protein and crops grown for starch. Since the current study compares the production methods of sugar beet alone, this concept is not used here, but the yield in each scenario was adjusted to account for differences in sugar concentration.

At present, organic production accounts for 0.2% of beet in the UK. Beet grown under organic methods on sandy loam had a low requirement for crop nutrition in comparison to the conventional scenarios, but a greater requirement for transport from the farm. We are probably overstating the energy efficiency of the organic scenario because the beet crop is using nitrogen fixed earlier in the rotation. In many cases, this will be nitrogen fixed by a legume that is grown solely for this purpose and we have made no allowance for the energy demands of this legume crop. Further, the requirement for off farm transport may have been underestimated slightly since it was assumed that all beet, whatever the production system, was mixed with the same proportion of soil and trash during delivery. Harvested organic beet is almost always mixed with more weeds than conventional beet that retain more soil and are also transported to the factory. Overall, the low yield of the organic scenario resulted in an additional energy input of 103 MJ/t compared to conventional beet grown on sandy loam using mineral fertiliser. The organic scenario also had the greatest GWP/t, although this was chiefly a result of the diesel consumed in transporting the harvested crop further to the factory than the conventional scenarios.

Many of the calculations and results in this paper rely upon the estimated yield of each scenario and we have used estimates that approximate to current mean yield values. It is our contention that this variation in yield is caused by a response to the amount of water available for growth, either as a result of differences in irrigation practice or of differences in soil type. In reality, variation in yields will occur despite adherence to the inputs specified for each scenario. Yields and thus energy output are greatly influenced by small and subtle shifts in, for example, the depth and time of seedbed cultivation and sowing, or the timing of herbicide applications. Further improvement in the energy efficiency of beet production will most likely be achieved by optimising the timing of such inputs to improve output and will be largely independent of the fossil energy input.

The UK beet crop produces between 7.3 and 15.0 times as much energy in dry matter at the sugar factory gate as consumed in its production, with an average ratio of 9.7. It has an average GWP of 0.024 eq. t CO_2 per tonne of clean beet harvested, equivalent to 0.0062 eq. t CO_2 per GJ output. The ratio for winter wheat grain has been calculated at between 6.0 and 13.0 (Keusters and Lammel, 1999), 8.9 (Richards, 2000) and 13.2 (Rathke and Diepenbrock, 2003). These ratios correspond to an estimated GWP of between 0.174 and 0.093 eq. t CO_2 per tonne, equivalent to 0.0109 and 0.0053 eq. t CO_2 per GJ output. The output/input ratio for winter oilseed rape has been determined at 7.67 (Richards, 2000) and 8.09 (Rathke and Diepenbrock, 2003), while a ratio of 4.5 was calculated for sunflower (Kallivroussis et al., 2002). Sugar beet may be a potentially good candidate to be grown for biofuel production in north-west Europe. Consideration however, must given to the entire biofuel production chain to include product processing not covered within the scope of this study. The availability of data that compares the efficiency of beet in the UK with crops produced in other regions of the world, such as sugar cane, is sparse. Austin et al. (1978) address this matter although the production methods and the energy associated with manufacture of inputs have since altered, quite considerably in cases such as fertiliser manufacture. To allow an accurate comparison of the two crops, a further study that considers present day production methods and input values is needed to compare UK beet with a similarly detailed assessment of sugar cane production.

5. Conclusions

Energy use within agriculture is considered to be a key indicator of sustainable development and the use of methods to mitigate its environmental impact is vital. Crop production methods that reduce energy input while maintaining output are important components of a sustainable agricultural system. In the UK, beet production on peat, silt or clay loam soils that are more water retentive and tend to produce larger yields, is preferable as a means of optimising energy efficiency and minimising the GWP from inputs. The energy efficiency of peat soil is however in part, due to the mineralisation of large amounts of organic matter to produce nitrate and ammonia, thus eliminating the need for N fertiliser. In the long term this process is not sustainable since the peat will gradually oxidise and eventually produce only small amounts of mineral N. Beet yields are greatly dependent upon the timing of input application thus any alteration in such a timing that increases yield will also increase the energy efficiency.

The output/input energy ratio of beet grown in the UK compares favourably to other arable crops grown in Europe, although its performance compared to sugar cane produced in the southern hemisphere requires quantification. The current study has only taken account of the energy input and output to the factory gate and has not considered differences between crops that may occur during the processing of the harvested product.

One aspect of the environmental impact of the UK sugar beet crop has been considered. A more holistic approach, to include an assessment of the nitrogen cycle and ecotoxicity of pesticides on wildlife, is also required.

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