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A model for fossil energy use in Danish agriculture used to compare organic and conventional farming

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Abstract

Knowledge about fossil energy use in agricultural systems is needed, because it can improve the understanding of how to reduce the unsustainable use of limited energy resources and the following greenhouse gas emissions. This study describes and validates a model to assess fossil energy use in Danish agriculture; gives an example of how the model can be used to compare organic and conventional farming; and discusses the implications and potentials of using the model to simulate energy use in scenarios of agricultural production. The model is a development of an existing model, which was too coarse to predict measured energy use on Danish farms. The model was validated at the field operational, the crop type, and the national level, and can supplement the Intergovernmental Panel on Climate Change manual to quantify fossil energy use and subsequent carbon dioxide emissions from agriculture. The model can be used to model energy use as one indicator in a multi-criteria evaluation of sustainability, also including other agroecological and socio-economic indicators.

As an example, energy use for eight conventional and organic crop types on loamy, sandy, and irrigated sandy soil was compared. The energy use was generally lower in the organic than in the conventional system, but yields were also lower. Consequently, conventional crop production had the highest energy production, whereas organic crop production had the highest energy efficiency. Generally, grain cereals such as wheat have a lower energy use per area than roughage crops such as beets. However, because of higher roughage crop yields per area, energy use per feed unit was higher in the roughage crops. Energy use for both conventional cattle and pig production was found to be higher than that for organic production. With respect to fossil energy use per produced livestock unit, agro-ecosystems producing pigs were in both cases less energy effective than those producing cattle.

Fossil energy use for three scenarios of conversion to organic farming with increasing fodder import was compared to current conventional farming in Denmark. The scenario with the highest fodder import showed the highest energy use per livestock unit produced. In all scenarios, the energy use per unit produced was lower than in the present situation. However, the total Danish crop production was also lower.

In conclusion, the model can be used to simulate scenarios, which can add new information to the discussion of future, sustainable agricultural production.

Keywords: Fossil energy; Diesel fuel; Organic farming; Agroecology; Denmark

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Abbreviations: SFU, Scandinavian feed units; LSU, Livestock units

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1. Introduction

The Nobel Prize winner Soddy (1933) connected the availability of energy to future prosperity, and the high rate of economical growth after the Second World War confirmed this (Hitzhusen, 1993). Access to cheap and plentiful fossil energy was an important reason for improved standards of living and increased food production in these years (Cleveland, 1995).

Problems with the use of fossil energy in agriculture came into focus with the pioneer studies of agricultural ecology (Odum, 1971), and was emphasised by the 1973 oil embargo and the following increased price of energy. Pimentel et al. (1973) revealed the degree to which increasing corn-yields (*Zea mays* L.) in the USA relied on increased use of inputs that reflected a high use of the limited fossil energy. However, recent calculations have revealed that if the captured solar energy was included in the Pimentel et al. (1973) account, there is no diminishing return to energy input from 1945 to 1985. Each extra joule of input returns an extra ca. 3 J of output (Evans, 1998).

Today, problems with the use of fossil energy in agriculture are again attracting interest; partly because fossil energy is a limited resource to be conserved for future generations (Brown et al., 1998), but mainly because of problems with emissions of the greenhouse gas carbon dioxide to the atmosphere (IPCC, 1997). Because of the increased emissions of greenhouse gases the global mean temperature has risen over the past 100 years and future impacts on the climate are uncertain (Pimentel et al., 1992; Flavin and Dunn, 1998).

The development of agricultural systems with low input of energy compared to the output of food could help to reduce agricultural carbon dioxide emissions (Dalgaard et al., 2000). In this context, the development of organic farming might be one possibility to save energy (Pimentel and Pimentel, 1996). Another possibility might be a lower level of animal production (Bleken and Bakken, 1997). To investigate these questions thoroughly, knowledge about energy use in different agricultural systems is needed. This knowledge can then be included in a multi-criteria evaluation of the sustainability of agricultural systems, including other agroecological (Barnett et al., 1994) and socio-economic (Opschoor and Reijnders, 1991) indicators of sustainability. Sustainability implies efficient use of non-renewable resources and the progressive substitution of renewable for non-renewable resources.

Recently, most efforts to quantify greenhouse gas sinks and sources in agriculture have concentrated on sources other than fossil energy (Sensi, 1999). This is despite the fact that burning fossil energy is responsible for about 30% of the greenhouse gas emissions from Danish agriculture (Dalgaard et al., 1999). Primary agriculture consumes about 5% of the total fossil energy used in Denmark (Ministry of Environment and Energy, 1995). Also on a global basis agriculture is responsible for about 5% of the total energy used (Pinstrup-Andersen, 1999).

There are very few models, that can be used to compare fossil energy use in different agricultural production systems (Plentinger and Penning de Vries, 1996). Also, the Intergovernmental Panel on Climate Change manual (IPCC, 1997) for calculating national greenhouse gas emissions does not include methods to quantify fossil energy use and subsequent carbon dioxide emissions from agriculture. The available models are either inventory models (McFate, 1983), or are too coarse to predict the energy use of farms (Refsgaard et al., 1998). Another problem with energy models is their extreme sensitivity to:

- The choice of the scale and the boundaries of the analysis (Dalgaard, 2000).
- The accuracy of the energy-use data. For example, the problem of assessing the fuel use, which is especially emphasised in this study.
- The goals of the analysis. For example, if you are mapping energy uses to track CO_2-emissions you will ignore large differences in efficiency of the CO_2-neutral production of electricity by nuclear plants and on the contrary, be very interested in small differences in conversion losses for electricity produced by coal plants.

The aims of this study is to: (1) describe a simple model to assess fossil energy use in agricultural systems; (2) to give an example of how this model can be used to compare energy use in organic and conventional crop, cattle and pig production and (3) to discuss the general implications and potentials of using the model to simulate fossil energy use as one of many indicators of sustainability in scenarios for agricultural production.

2. Materials and methods

2.1. Definition of the method for energy analysis

This study uses The United Nations Food and Agriculture Organisation's definition of basic energy concepts (Hulscher, 1991), which relies on the energy analysis suggested by International Federation of Institutes for Advanced Studies (IFIAS, 1974).

Energy (E) is defined as fossil energy measured in joule (J). All fuels and electricity are posited to come from fossil energy sources. Energy use (EU) is defined as the net energy used for production of an agricultural product until it is sold and leaves the farm, or is used as fodder for livestock. Energy use can be divided into direct and indirect EU (Uhlin, 1998). Direct EU is energy input used in production when such input can be directly converted into energy units (e.g. diesel-fuel, lubricants and electricity for irrigation and drying). Indirect EU is energy used in the production of inputs used in production when such inputs cannot be converted directly into energy units (e.g. machinery, fertilisers, and pesticides would come into the latter category). In the following sections, the models used to calculate EU are explained.

2.2. A model for energy use in the crop production

The crop production energy model is divided into six sub-models for the use of diesel, three sub-models for direct EU other than diesel, and two sub-models for indirect EU (Table 1). Thus, the total EU for growing a specific crop ($\mathrm{EU_{crop}}$) can be expressed by Eq. (1):

$$\begin{aligned}\mathrm{EU_{crop}} &= \mathrm{EU_{direct}} + \mathrm{EU_{indirect}} \\ &= (\mathrm{EU_{diesel}} + \mathrm{EU_{other}}) + \mathrm{EU_{indirect}}\end{aligned} \tag{1}$$

2.2.1. Diesel use

The six sub-models for diesel use represent six categories of field operations. For each field operation (n), there is a corresponding norm (D_n) for the use of diesel. Each norm is a linear function of either the area treated, or the amount input factor applied, or the weight of crop harvested, or the distance to the field operation. For example, the norm for ploughing is litre per hectare, the norm for mowing is litre per tonne, and the norm for manure transport is litre per tonne per kilometre (Table 2).

D_n are selected on the basis of the referenced literature, and diesel use monitored for selected operations on private, Danish dairy farms. On these farms, use of diesel for field operations was measured by the farmer with a diesel flow meter. The use of diesel is measured in litre but can be converted to megajoule by multiplication with $35.9\,\mathrm{MJ\,l^{-1}}$, which is the energy released when 1 l diesel is totally combusted. To this, subsequently added $5\,\mathrm{MJ\,l^{-1}}$ oil equivalent for the distribution and extraction of the fuel (de Boo, 1993). The D_n-norms for soil preparation (tilling, sowing and mechanical weed control) are corrected for soil type by a factor of 1.1 for a loamy soil (primarily *Cambisols* and *Luvisols*), a factor of 1.0 for a sandy-loamy soil (primarily *Arenosols* and *Cambisols*) and a factor of 0.9 for a sandy soil (primarily *Podzols*) (Breuning-Madsen and Jensen, 1996). In this study, a distance of 1 km

Table 1
Components in the model for the use of fossil energy in crop production

Direct energy		Indirect energy ($\mathrm{EU_{indirect}}$)
Diesel for farm operations ($\mathrm{EU_{diesel}}$)	Other direct energy ($\mathrm{EU_{other}}$)	
Tillage and sowing	Lubrication	Machinery
Fertilising and liming	Field irrigation	Other external inputs (nitrogen, phosphorus, potassium, lime and pesticides)
Plant protection	Drying	
Harvesting and baling		
Transport		
Loading and handling		

Table 2
Norms for diesel use in crop production (D_n) compared to values found in the referenced literature or monitored on private farms

Operation	Unit	D_n norm[a]	Literature		Monitored diesel use		
			Low-high[b]	Reference[c]	Average	Low-high[b]	No[d]
Tilling and sowing							
Ploughing (21 cm), spring	l ha^{-1}	20.0	8.4–32.7	1, 2, 4	17	12.0–22.0	9
Ploughing (21 cm), autumn	l ha^{-1}	23.0	8.4–32.7	1–6	22	15.0–27.0	16
Soil compaction	l ha^{-1}	2.0	1.8	1, 2			
Seedbed harrowing, light	l ha^{-1}	4.0	2.2–4.7	1, 2, 4, 5			
Seedbed harrowing, heavy	l ha^{-1}	6.0	4.9–16.8	1, 2, 4, 5	6.2	4.9–7.1	3
Rolling	l ha^{-1}	2.0	1.8	1	1.6		1
Sowing	l ha^{-1}	3.0	0.9–21.6	2, 4	3.2	3.0–3.4	2
Stubble cultivation	l ha^{-1}	7.0	2.8–30.9	3, 4	7.3	4.0–18.0	7
Fertilising and liming							
Spreading and loading manure	l t^{-1}	0.6	0.4–1.8	5, 8	0.6	0.5–0.7	4
Spreading slurry	l t^{-1}	0.3	0.2–1.1	3, 5	0.5	0.3–3.7	7
Spreading fertiliser	l ha^{-1}	2.0	0.9–4.7	3–5, 8	1.9		1
Liming	l ha^{-1} per year	1.5					
Plant protection							
Pesticide spraying	l ha^{-1}	1.5	0.8–1.7	3–5	1.2	1.1–1.4	2
Weed harrowing	l ha^{-1}	2.0	1.5–2.4	3			
Row listing	l ha^{-1}	3.0	3.0–4.9	3, 5			
Harvesting and baling							
Combine harvesting	l ha^{-1}	14.0	7.0–19.0	3–5, 8	14	11.0–19.0	20
Sugar beet harvesting	l ha^{-1}	17.0	8.4–22.0	4, 5, 10, 12, 13	13		1
Cutting, sugar beet top	l ha^{-1}	10.0	7.8–21.0	4, 8, 12, 13	10	7.4–13.0	4
Mowing	l ha^{-1}	5.0	5.3–10.4	5	8.0	5.0–27.0	2
Baling (high pressure) + handling	l t^{-1}	1.5 + 0.5	1.3–1.7	2, 5, 8	1.6		
Mowing	l t^{-1}	0.5	0.3–0.9	5, 14, 15			
Stalk breaking	l t^{-1}	+0.2		10			
Chopping	l t^{-1}	1.0	0.7–2.1	13–15	1.7	1.2–3.3	4
Transport							
Machine transport	l km^{-1}	0.04	0.3–0.4[e]	14	1.2[e]	0.2–2.3[e]	3
Manure and fodder transport	l t^{-1} km^{-1}	0.2	0.1–0.5	8, 14	0.4[e]	0.3–0.5[e]	3
Loading and handling							
Loading	l t^{-1}	0.3	0.1–0.5	8, 14	0.3	0.2–0.3	5
Loading and handling	l t^{-1}	0.5	0.3–1.1	14			
Feeding	l t^{-1}	0.3	0.1–0.4	14			
Other handling	l t^{-1}	0.5					
Handling (total average)	l t^{-1}	1.3	0.3–3.8	14	1.6	1.1–2.1	41

[a] The showed D_n-norm are not corrected for soil type.

[b] Low-high are the lowest and highest values found.

[c] 1: Nielsen, 1987, 2: Nielsen, 1989, 3: Nielsen and Sørensen, 1994, 4: Stout et al., 1982, 5: McFate, 1983, 6: Vitlox and Pletinckx, 1989, 7: Brown, 1988, 8: Pick and Netik, 1989, 10: White, 1974, 12: Pick, 1984, 13: Nielsen, 1985, 14: Nielsen, 1991, 15: Cunney, 1982.

[d] No is the number of field measurements on private farms.

[e] Inclusive of loading.

Table 3
Norms for the use of energy other than diesel

Input	Unit	Norm	Low-high[a]	Reference[b]
Lubricants (L)	MJ l^{-1} diesel	3.6	3.6–5.7	1
Machinery (M)	MJ l^{-1} diesel	12		7, 9
Field irrigation (I)	MJ mm^{-1}	52		1, 3
Drying (R)	MJ t^{-1} per %-point	50		4, 6
Nitrogen, synthetic (E_1)	MJ kg^{-1} N	50	43–78	3, 4, 11, 12, 19
Phosphorus, synthetic (E_2)	MJ kg^{-1} P	12	12–17	4, 11, 12, 19
Potassium, synthetic (E_3)	MJ kg^{-1} K	7.0	6.0–14	4, 11, 12, 19
Lime (E_4)	MJ t^{-1}	30		1
Herbicides (E_5)	MJ kg^{-1}	40[c]	80–460[d]	16, 17, 18
Insecticides (E_5)	MJ kg^{-1}	40[c]	58–580[d]	16, 17, 18
Fungicides (E_5)	MJ kg^{-1}	40[c]	61–397[d]	16, 17, 18

[a] Low-high are the lowest and highest values according to the referenced literature.

[b] 1: Refsgaard et al., 1998, 3: Pimentel, 1980, 4: Leach, 1976, 6: Cunney, 1982, 7: Sonesson, 1993, 9: Bowers, 1992, 11: Hjortshøj and Rasmussen, 1977, 12: Bøckman et al., 1991, 16: Stout et al., 1982, 17: Green, 1987, 18: Fluck, 1992, 19: Mudahar and Trignett, 1987.

[c] Per kilogram formulated agent.

[d] Per kilogram active agent.

in transportation to the fields is assumed for each operation.

If N is the total number of operations for growing a specific crop, and CD_n is the diesel use per ha for each of these operations, calculated according to the norms above, the total energy use per ha in the form of diesel can be expressed as follows:

$$\mathrm{EU}_{\mathrm{diesel}} = \sum_{n=1}^{N} \mathrm{CD}_n \tag{2}$$

2.2.2. Other direct energy use

Other direct energy use includes energy for lubrication (L) and for drying (R) and irrigation (I) of crops (Table 3). Lubrication is linear with the use of diesel, whereas I is linear with the amount used irrigation water (AI). Finally, R is linear with the weight of crops dried (AD), and the percentage of drying (PD) expressed as the decrease in weight of the crop harvested caused by drying. In this study, PD is set to 2%-point.

$\mathrm{EU}_{\mathrm{other}}$ measured in megajoule per hectare can, analogous to $\mathrm{EU}_{\mathrm{diesel}}$, be calculated by formula (3):

$$\mathrm{EU}_{\mathrm{other}} = \sum_{n=1}^{N} \mathrm{CD}_n \times L + (\mathrm{AD}_n \times \mathrm{PD}_n \times R) + (\mathrm{AI}_n \times I) \tag{3}$$

2.2.3. Indirect energy use

The sub-models for indirect energy uses include energy for machinery (M) and energy for external input of nitrogen (E_1), phosphorus (E_2), potassium (E_3), lime (E_4) and pesticides (E_5). Machinery is lineally related to the use of diesel, whereas the indirect energy (E_i) per weight of nitrogen ($i = 1$), phosphorus ($i = 2$), potassium ($i = 3$), lime ($i = 4$), and spraying agents ($i = 5$) are linear with the total amount used of each of these input (AE_i) (Table 3). The $\mathrm{EU}_{\mathrm{indirect}}$, measured in megajoule per hectare, can thereby in line with $\mathrm{EU}_{\mathrm{diesel}}$ and $\mathrm{EU}_{\mathrm{other}}$ be calculated via formula (4):

$$\mathrm{EU}_{\mathrm{indirect}} = \sum_{n=1}^{N} \mathrm{CD}_n \times M + \sum_{i=1}^{5} \mathrm{AE}_i \times E_i \tag{4}$$

2.3. Crop production in Denmark

The $\mathrm{EU}_{\mathrm{crop}}$ was calculated for the following crop types: spring grain cereals (*Hordeum vulgare*), winter grain cereals (*Triticum aestivum*), spring whole crop cereals (*Hordeum vulgare*), winter cereals (*T. aestivum*), fodder beets (*Beta vulgaris*), grass/clover (*Lolium* sp./*Trifolium* sp.) and straw. For each crop type, a standard number and types of operations were assumed.

For each crop type yields for organically and conventionally growing practice were estimated (Halberg and Kristensen, 1997). Gross yields in Scandinavian feed units (1 SFU = 12 MJ of metabolisable energy, equivalent to the fodder value in 1 kg barley) were converted to dry weight in kilogram (Strudsholm et al., 1997). Net yields were calculated by subtraction of the seeds sown; 160, 180, 50 and 25 SFU $\mathrm{ha^{-1}}$ per year for spring cereals, winter cereals, fodder beets and clover grass, respectively. The calculated crops were fertilised according to standard Danish practice, where conventionally grown crops were presumed to have mineral fertilisers applied so that Danish norms for N-fertilisation were attained. For instance, the addition norm for barley for a loamy soil in the west of Denmark is 124 kg plant available NO_3-N per hectare after cereals and 94 kg $\mathrm{ha^{-1}}$ after grass/clover. Organic farms had a livestock density corresponding to 1.1 LSU $\mathrm{ha^{-1}}$ and the conventional farms had 1.8 LSU $\mathrm{ha^{-1}}$, where 1 LSU corresponds to one large-breed dairy cow in 1 year, or 30 slaughter pigs produced (Dalgaard et al., 1998). The distribution of the farm manure on crops was set according to Halberg and Kristensen (1997). Longer outdoor periods for animals on organic farms gave more animal manure deposited directly on the fields and relatively less slurry to be spread per animal. With the high livestock density used, no input of mineral P or K was needed. All crops received 0.75 mg lime per year. On sandy soils, spring cereals were irrigated with 45 mm, winter cereals with 53 mm, fodder beets with 75 mm and grass/clover with 133 mm of water (Refsgaard et al., 1998). For conventional crops the amounts of sprayed, formulated pesticides were assumed to be 3.0 kg $\mathrm{ha^{-1}}$ for grain spring cereals, 5.0 kg $\mathrm{ha^{-1}}$ for grain winter cereals, 5.8 kg $\mathrm{ha^{-1}}$ for fodder beets, 1 kg $\mathrm{ha^{-1}}$ for whole crop spring cereals, 2.5 kg $\mathrm{ha^{-1}}$ for whole crop winter cereals and 1 kg $\mathrm{ha^{-1}}$ for grass/clover.

2.4. A model for energy use in dairy and pig production

The EU for production of cattle and pigs was calculated as the sum of indirect energy for operations in the livestock housing (*S*), heating of the livestock housing (*H*), farm buildings, inventory, etc. (*B*), imported fodder (*F*) and self-produced fodder (*O*) (Table 4). Operations in the livestock houses include light, ventilation, milking, milk cooling, fodder milling and pumping (The Danish Producers of Electricity, 1994). The difference between organic and conventional pig production was because no fossil energy for ventilation or heating was used in the livestock houses on organic pig farms.

Table 4
Norms for the fossil energy use (EU) in cattle and pig production

	Unit[a]	Norm	Low-high	Reference[b]
Operations in livestock houses (*S*)				
For dairy cows	GJ $\mathrm{LSU^{-1}}$	8.0	–	2, 7
For other cattle	GJ $\mathrm{LSU^{-1}}$	1.7	–	2, 7
For conventional sows	GJ $\mathrm{LSU^{-1}}$	6.1	–	2, 7
For organic sows	GJ $\mathrm{LSU^{-1}}$	3.2	–	2, 7
For conventional slaughter pigs	GJ $\mathrm{LSU^{-1}}$	0.9	–	2, 7
For organic slaughter pigs	GJ $\mathrm{LSU^{-1}}$	0.4	–	2, 7
Heating of livestock houses (*H*)				
For conventional sows	GJ $\mathrm{LSU^{-1}}$	3.1[c]	–	7
For conventional slaughter pigs	GJ $\mathrm{LSU^{-1}}$	0.6[c]	–	7
Farm buildings, inventory, etc. (*B*)	GJ $\mathrm{LSU^{-1}}$	2.5	–	1, 7
Imported fodder (*F*)	MJ $\mathrm{SFU^{-1}}$	5.7	1.4–7.7	1, 4
Own fodder produced (*O*)[d]	MJ $\mathrm{SFU^{-1}}$	$\mathrm{EU_{crop}}$/yield	0.2–3.7	7, 8

[a] 1 LSU corresponds to 1 large-breed dairy cow in 1 year, or 30 slaughter pigs produced. 1 SFU = 12 MJ metabolisable energy (1 kg barley equivalent).

[b] 1: Refsgaard et al. (1998), 2: The Danish Producers of Electricity (1994), 4: Cederberg (1998), 7: Dalgaard et al. (1999), 8: Section 2.2.

[c] Eighty percent of the standard norm because ca. 20% of pig production is non-heated.

[d] Calculated using the models in Section 2.2.

The total EU ex farm per livestock unit cattle or pig ($\mathrm{EU}_{\mathrm{animal}}$) can, like $\mathrm{EU}_{\mathrm{crop}}$, be divided into direct and indirect EU, and calculated via the following Eq. (5).

$$\begin{aligned}\mathrm{EU}_{\mathrm{animal}} &= \mathrm{EU}_{\mathrm{direct}} + \mathrm{EU}_{\mathrm{indirect}}\\ &= (S + H) + (B + F + O) \qquad (5)\end{aligned}$$

2.5. Animal production and scenarios for conversion to organic farming in Denmark

The Bichel Committee (1999) compared the 1996 Danish animal production with three scenarios (A–C) for conversion to 100% organic farming in Denmark:

1. Full self-supply with fodder (e.g. no fodder is imported to the country). Hereby the pig production is limited.
2. Fifteen percent import of fodder for ruminants, and 25% for non-ruminants. Pig production is also limited but less than in scenario A.
3. Maintenance of the present (1996) animal production via unlimited import of fodder.

For the 1996 situation and the three organic scenarios, the animal production of Denmark was simplified to consist of cattle and pigs (Table 5). In the scenarios, cattle were further divided into, cows, breeding stock, bullocks and bulls. Pigs were divided into sows and slaughter pigs.

The vegetable production, needed to supply the animal production with fodder, was simplified to four crop types (Table 6). For each crop type, $\mathrm{EC}_{\mathrm{crop}}$ was calculated as weighted averages of the soil types described in Section 2.3, where the area distribution of soils in Denmark is 39% loamy soils, 10% sandy soils and 51% irrigated sandy soils (Bichel Committee, 1999). Synthetic fertiliser use was corrected to the total national use according to Statistics Denmark (1996). The crop type grass/clover was defined as 50% grass/clover for pasture and 50% grass/clover for silage. Crop type cereals (grain) was defined as 50% winter cereals (grain) and 50% spring cereals (grain), including the straw from these crops. Row crops were defined as fodder beets, and permanent grass was defined as organically grown grass/clover for pasture on sandy, non-irrigated soil. To obtain an average national figure for the defined crop types, the EU ex farm was added to the energy cost for the distribution and extraction of fuels ($5\,\mathrm{MJ\,l^{-1}}$ diesel equivalent; de Boo, 1993). Because the national sum of simulated energy (SI) for fuels, electricity and machinery differs from the energy used according to national statistics (ST), the simulated EU for each crop type was corrected

Table 6
The crop production (10^6 ha) in 1996 (conventional farming) and in the three scenarios for conversion to 100% organic farming in Denmark

Crops	Conventional farming	Organic farming
Grass/clover	0.3	1.0
Cereals	1.6	1.3
Row crops	0.4	0.2
Permanent grass	0.4	0.2
Total	2.7	2.7

Table 5
The animal production (10^5 LSU) in three scenarios for conversion to 100% organic production in Denmark compared to the 1996 situation with conventional farming (after Dalgaard et al., 1999)

Livestock	1996 Situation	Organic scenarios		
		A: fodder self supply[a]	B: 15/25% fodder import[b]	C: production as in 1996[c]
Cattle	13	13	13	13
Pigs	10	4	8	11
Total	23	17	21	24

[a] Full self supply with fodder (e.g. no fodder is imported to the country). Hereby the pig production is limited.

[b] Fifteen percent import of fodder for ruminants, and 25% for non-ruminants. Hereby the pig production is limited but less than in scenario A.

[c] Maintenance of the present (1996) animal production. Unlimited import of fodder.

Table 7
Simulated total energy use for agricultural production in Denmark 1996 compared to national statistics

	PJ fossil energy		Correction-factor (CF = ST/SI)
	Simulated (SI)	Statistics (ST)[a]	
Direct energy use			
Fuels	18.0	19.3	1.1
Electricity	12.5	12.7	1.0
Indirect energy use			
Fertilisers, pesticides, etc.	14.5	13.9	1.0
Machinery	4.4	4.6	1.1
Buildings	5.7	6.3	4.1
Import of fodder	20.0	20.0	1.0
Total energy use	75.1	76.8	

[a] The Danish Energy Agency (1997) and Danish Farmers Unions (1998).

with the factor CF = ST/SI (Table 7). Finally, with the above definitions and information on animal and vegetable production, the received import of fodder was calculated.

3. Results

3.1. Energy use for crop production

The EU model was used to simulate $\mathrm{EU}_{\mathrm{crop}}$ compared to the crop yields for conventionally and organically grown crops on loamy soil, sandy soil, and irrigated sandy soil (Fig. 1).

Subsequently, these simulated figures were used to find the energy use ($\mathrm{EU}_{\mathrm{crop}}$) for the four crop types used in the scenarios for organic farming in Denmark (Fig. 2).

3.2. Energy use for animal production — scenarios for conversion to organic farming

Using the presented model, EU for the specified animal types were calculated for conventional and organic farming in Denmark, and grouped in EU for cattle (ruminants) and pigs (non-ruminants) (Fig. 3). Similar to the simulation of energy for crop production, the EU ex farm was corrected according to the CF-values (Table 7) after addition of energy costs for fuel distribution and extraction (Section 2.2.1).

4. Verification of results

The model was verified on three levels: (1) the field operation level; (2) the crop type level and (3) the national level.

At the field operation level, diesel use for field operations was monitored on private farms and the results was compared to literature (Section 2.2.1). The monitored diesel use was within the range of that found from literature values, thus the selected figures and units for the D_n-norms appear appropriate.

At the crop type level, the simulated EU for fuel (diesel and lubricants) was compared to independent measurements by Refsgaard et al. (1998) (Fig. 4). In Refsgaard et al. (1998), the fuel use according to 2 years of farm accounts from 31 private farms was recorded and compared to expected fuel use according to standard values for grown crop types. On average, the farms used 47% more fuel than expected. The fuel not accounted for was consequently added proportionally to the standard fuel use for each crop type. This gives the corrected fuel use (CFU). This procedure may for some crops result in a CFU-value that overestimates the actual fuel use, while for others, CFU may underestimate the actual fuel use. In particular, fuel use for growing fodder beets and grass/clover (silage) was probably underestimated, whereas that for growing whole crops and grass/clover (pasture) was overestimated (Fig. 4). The primary cause of this error is a systematic underestimation of EU for transport and handling of roughage crops and animal manure in

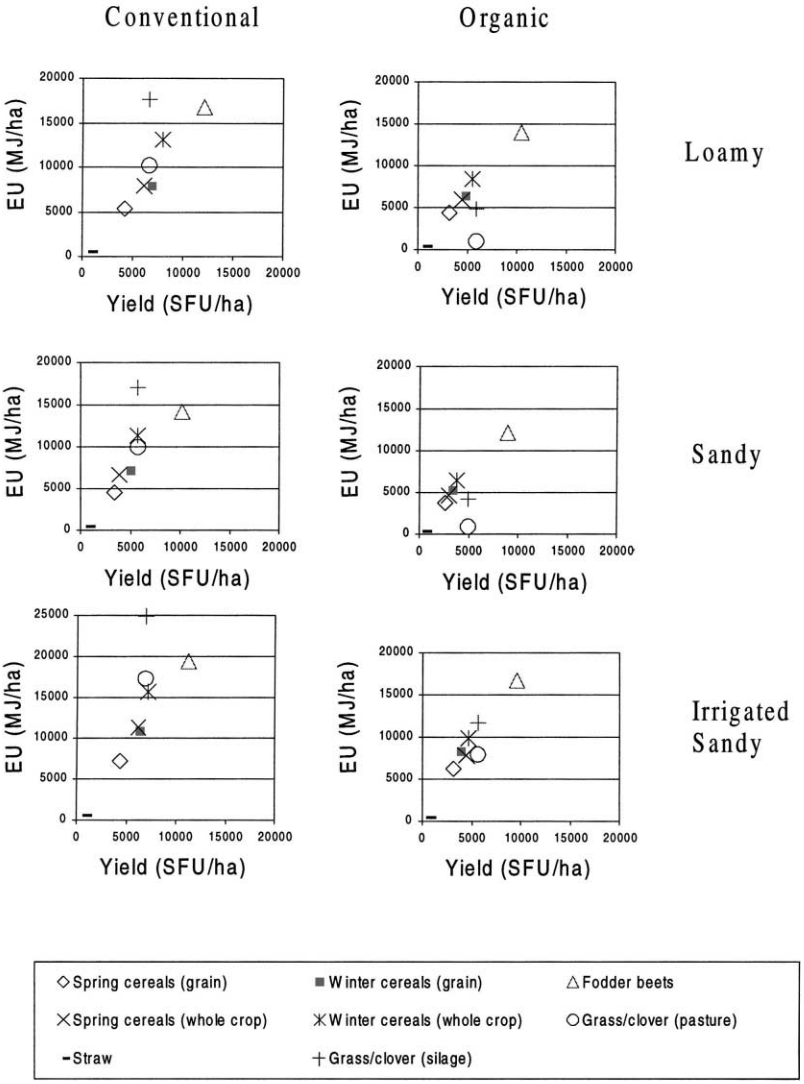

Fig. 1. Simulated energy use (EU) compared to the crop yields for conventionally and organically grown crops on loamy soil, sandy soil, and irrigated sandy soil. 1 SFU = 12 MJ of metabolisable energy, equivalent to the fodder value in 1 kg barley.

Refsgaard et al. (1998). The modelled fuel use for grain cereals did not differ significantly from the CFU values. It is concluded from this comparison, that there are no large differences between the modelled fuel use figures and the measured fuel use, CFU, according to Refsgaard et al. (1998).

At the national level, simulated EU in the 1996 situation (SI) was compared to the EU according to statistics (ST) (Table 7). The difference between SI and ST was below 12% (Dalgaard et al., 2000). Considering the coarse scenarios this difference is insignificant, and a good proof of the suitability of the present model.

The direct energy for fuels was calculated as the sum of energy in diesel and lubricants for the grown crops plus the energy for heating of pig houses, including the 5 MJ l^{-1} oil equivalent for the distribution and extraction of the fuel (de Boo, 1993). The rest of the direct energy use was accounted for as electricity.

Indirect energy use (ST) was calculated from the same figures and norms as SI, and was not actually

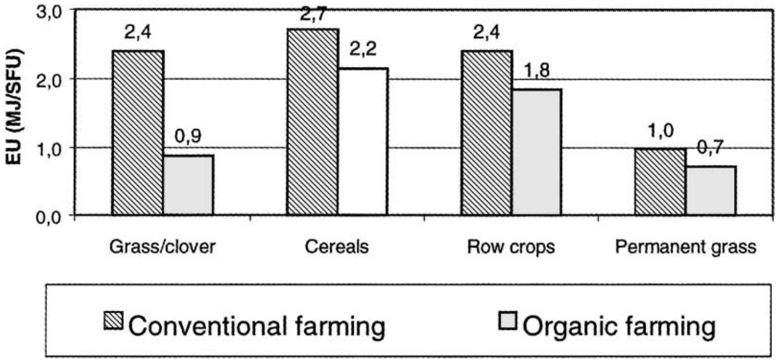

Fig. 2. Average national energy use (MJ SFU^{-1}) for the four crop types in conventional farming (the 1996 situation), and in the scenarios for 100% organic farming in Denmark. 1 SFU = 12 MJ of metabolisable energy, equivalent to the fodder value in 1 kg barley.

independent from the statistics. The EU for nitrogen fertilisers was calculated from the used kilogram N according to the national statistics multiplied by the norm of 50 MJ kg^{-1} N (Table 3), because the statistics did not include indirect EU, but only the amount of used input factors containing the energy (Danish Farmers Unions, 1998). The differences between the indirect EU values of ST and SI, therefore, indicate differences between the real 1996 situation and the set up scenario for the 1996 situation, in terms of amounts used of the different items.

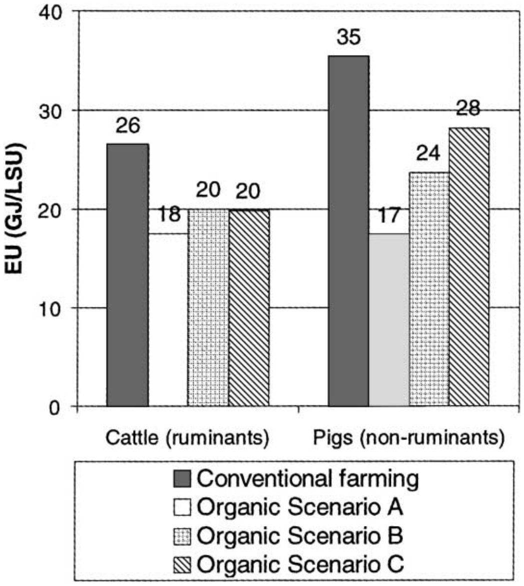

Fig. 3. Simulated energy use (EU) for ruminants and non-ruminants in the 1996 situation (conventional farming) compared to three scenarios for conversion to 100% organic farming. (A) Full self-supply with fodder (e.g. no fodder is imported to the country). Hereby the pig production is limited. (B) Fifteen percent import of fodder for ruminants, and 25% for non-ruminants. In this scenario, the pig production is limited but less than in scenario A. (C) Maintenance of the present (1996) animal production with an unlimited import of fodder. One LSU corresponds to 1 large-breed dairy cow in 1 year or 30 slaughter pigs produced.

5. Discussion

5.1. The model for energy use

A simple model for simulation of fossil energy use (EU) in agricultural production was used to compare EUs for conventional and organic farming in Denmark. The model may be extrapolated to other similar countries in the temperate climate zone (Section 5.2), but simulations with local figures for field treatments, input factors and yields are recommended. The model may also be used to simulate other crop and animal types than presently shown, if the needed input data are available. For instance, Kuemmel et al. (1998) used a preliminary version of this model to simulate EU for diesel use in a combined food and energy cropping system, and Halberg (1999) similarly accounted for 3 years EU for grain production on 20 private farms.

5.1.1. Fuel use

The model seems especially able to simulate fuel use. Compared to measurements at the crop type level, the present model was able to account for all

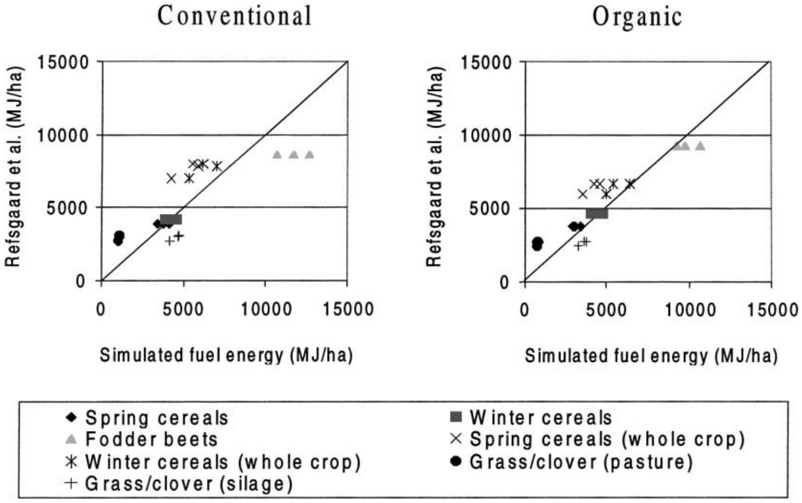

Fig. 4. Simulated fuel energy use obtained for different crops with the present model versus independently measured fuel energy use (CFU) according to Refsgaard et al. (1998). For each crop, the highest simulated figures are for loamy soil, the second highest are for irrigated, sandy soil, and the lowest figures are for non-irrigated, sandy soil. Figures are shown for conventional and organic farming practice.

fuel use, including the 47% not accounted for in Refsgaard et al. (1998). This was achieved by an extension of the norm-table (Table 2). Here, fuel use was made a linear function of area treated, amount handled, soil type and distance transported, depending on which variables were important for the actual operation on the farms where the fuel use was measured. No non-linearities were included in the model. For instance, fuel use is a non-linear function of field size (Nielsen and Sørensen, 1994), but because field size was not included in the present model, it was assumed that the fields have the same average size distribution in organic and conventional farming. Also factors like the size of the vehicles used for transport, sizes of the machines, soil moisture, the terrain, and the tractor driving technique might differ between farm types, but were not included in the present model. Fig. 4 showed that estimated fuel use for fodder beets were higher according to the present model than according to Refsgaard et al. (1998), whereas the opposite was the case for grass/clover pasture. The explanation for this is probably that the 47% of fuel not accounted for in Refsgaard's model is divided proportionally between the simulated crop types, and consequently fuel use for some crops was overestimated compared to the actual use, while that for others was underestimated.

5.1.2. Other energy use

Based on literature values, the sub-models for other direct energy uses than fuel, are not as detailed as the fuel use model. For instance EU for machinery was assumed to be a linear function of the fuel use. This simple approach was found to be better than the earlier Refsgaard et al. (1998) method, which was based on Fluck (1992), estimated EU from the weight and life expectancy of the machinery. This simplification was chosen partly because it excludes the uncertainty of these variables and partly because these variables are difficult to measure on larger scales than a single farm. The EU standards for fertilisers and pesticides are at the lower end of the interval found in the literature because the latest literature indicates decreased EUs caused by higher efficiency in the chemical industry.

The model for indirect EU was difficult to verify in practice and relied solely on literature studies (Table 3). However, a consensus about indirect EU in the form of input factors used in the agricultural sector is growing, especially with the latest initiatives on harmonisation of life-cycle assessments (e.g. The European Commission, 1997; Cederberg, 1998; Weidema and Meeusen, 1999). It will be straightforward to extend the present model with new or more detailed norms for indirect EU.

5.2. Energy use for crop production

Several authors have compared EU for organic and conventional crop production. For instance, Pimentel et al. (1983) found an EU, respectively, 10.0 and 7.2 GJ ha^{-1}, for conventionally and organically grown spring wheat in North Dakota. For Danish conditions, Vester (1995) calculated the EU of spring barley on organic model farms (6.9–13.0 GJ ha^{-1}) and on conventional farms (15.4–21.2 GJ ha^{-1}). Also in Denmark, Refsgaard et al. (1998) found EU values for organically and conventionally crop production (Fig. 4). Leach (1976) calculated typical EUs in the UK and found an EU of 15.7 GJ ha^{-1} for spring barley, 26.4 GJ ha^{-1} for the row crop maize, and 15.6–18.9 GJ ha^{-1} for wheat. Finally, Mörschner and Bärbel (1999) have estimated a total EU of 16.8 GJ ha^{-1} for growing conventional winter wheat in Germany, compared to Tsatsarelis (1993) estimation of 16.1–26.1 GJ ha^{-1} for conventional soft winter wheat production in Greece. All these values are within the range of this study's results (Fig. 1), and indicates that the present model could be used in these and similar geographical areas. Fig. 1 showed some relations between EU and average observed yields (Halberg and Kristensen, 1997), depending on crop type, farming system and soil type. In the conventional system, grass/clover (silage) had the highest EU compared to the yield. This was mainly because of the high use of synthetic fertiliser, but also because of a high EU for harvesting and handling of the silage (e.g. pastured grass/clover has a lower EU). In the organic system, fodder beets had the highest EU compared to yield. This was also because of a large EU for harvesting and handling, and the highest EU for spreading and handling of manure. Generally, the grain cereals (including straw) had a lower EU per area than the roughage crops, but because of higher roughage crop yields, it was the opposite to EU per feed unit. This was because of the lower EU for harvesting and handling of the grains, which per feed unit weigh less than roughage. The only exception to this was organically grown grass/clover (pasture), where pasturing on the field saved fuel both for harvesting and fertilising.

The energy efficiency (EE), calculated as the yield (SFU ha^{-1}) divided by the EU (MJ ha^{-1}), was generally higher in the organic system than in the conventional system (Fig. 2), but the yields were also lower (Fig. 1). Consequently, conventional crop production had the highest net energy production, whereas organic crop production had the highest EE. A closer look at Fig. 2 showed that the highest EEs were found for the extensively grown crops (1.0–1.4 SFU MJ^{-1} for permanent grassland, and 1.1 SFU MJ^{-1} for organically grown grass/clover). On the contrary, the more intensively grown, rotational crops had a low EE (0.4–0.6 SFU MJ^{-1} for row crops, and 0.4–0.5 SFU MJ^{-1} for cereals).

5.3. Energy use for animal production

All scenarios for conversion to organic farming showed a lower EU for production of both cattle and pigs than the 1996 situation (Fig. 3). Cederberg (1998) found the same for dairy production in Sweden: 22.0 GJ LSU^{-1} conventional cow ex farm, and 17.1 GJ LSU^{-1} organic cow ex farm. Also Halberg (1999) found, in a study of 15 Danish dairy farms over a 3-year period, a significantly lower EU for organically compared to conventionally produced milk.

Both in the 1996 situation and in the organic scenarios, simulated EUs were lower for ruminants (18–26 GJ LSU^{-1} cattle) than for non-ruminants (17–35 GJ LSU^{-1} pigs). This is basically because cattle eat proportionally more of the energy cheap roughage fodder and grass, while pig production is dependent on a high input of energy expensive grains and imported fodder.

Pimentel and Pimentel (1996), and Edwards et al. (1993) have both argued that agro-ecosystems producing non-ruminants are generally less energy efficient than agro-ecosystems with ruminants. In contrast, Uhlin (1998) in a Swedish study found that pig production required less solar energy input per megajoule metabolisable energy (ME) produced, than milk and beef production. This difference can be explained by differences in units, as 1 LSU dairy cow only represents about two-third of the ME from 1 LSU pig (Madsen and Petersen, 1981). The method to account energy input was also different in the two studies. To compare EU for cattle and pig production per megajoule of ME can be misleading, because the products (milk and beef versus pig meat) are unequal. Also, some of the land used for production of feed for ruminants (e.g. meadows and highlands with permanent grassland) cannot be used for the production of feed for non-ruminants.

5.4. Scenarios for conversion to organic farming

Both the EU for crop and animal production were lower in the organic scenarios than in the 1996 situation.

The organic scenario (C), in which animal production was maintained, showed the highest EU for animal production, while the scenario (A), with 100% fodder self supply, showed the lowest EU (Fig. 3). This is because the higher pig production in scenario C required a higher, energy expensive import of fodder than in scenario A and B. The lower EU in scenario C compared to EU in the 1996 situation was a result of that domestically produced, organic fodder was energetically cheaper than conventional fodder (Fig. 2, Table 4).

6. Conclusions

The presented model for calculation of fossil EU is suited for comparison of EU in organic and conventional crop, cattle and pig production, and represents an improvement compared to existing models.

Generally, EU per area for growing grain cereals was lower than that for growing roughage crops, but because of higher roughage crop yields, it was the opposite with EU per feed unit. For animal production, simulated EU per livestock unit was lower for cattle than for pigs.

The EU per unit crops and animals produced was lower in the scenarios for organic farming than for conventional farming. However, the total Danish crop production was also lower.

In conclusion, the presented model for fossil EU can be used to simulate scenarios for future agricultural production and can supplement the Intergovernmental Panel on Climate Change manual to calculate national greenhouse gas emissions. Both on the farm and national levels, such scenarios can give an essential basis for the choice of a future, sustainable agricultural production.

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References

Barnett, V., Landau, S., Welham, S.J., 1994. Measuring sustainability. Environ. Ecol. Stat. 1, 21–36.

Bichel Committee, 1999. Rapport fra den Tværfaglige økologigruppe (Report from the interdiciplinary group on organic farming). Report from The Danish Environmental Protection Agency, Copenhagen, ISBN 87-7909-292-6, 98 pp.

Bleken, M.A., Bakken, L.R., 1997. The anthropogenic nitrogen cycle in Norway. In: Romstad, E., Simonsen, J., Vatn, A. (Eds.), Controlling Mineral Emissions in European Agriculture, Vol. 2. CAB International, Wallingford, pp. 27–40.

Bowers, W., 1992. Agricultural field equipment. In: Fluck, R.C. (Ed.), Energy in Farm Production, Vol. 10. Elsevier, Amsterdam, ISBN 0-444-88681-8, pp. 117–129.

Breuning-Madsen, H., Jensen, N.H., 1996. Soil map of Denmark according to the revised FAO legend 1990. Danish J. Geogr. 96, 51–59.

Brown, R.H., 1988. Crop production engineering, In: Handbook of Engineering in Agriculture, Vol. I. CRC Press, Boca Raton, FL, ISBN 0-8493-3861-1, 261 pp.

Brown, L.R., Flavin, C.F., French, H., 1998. State of the World. W.W. Norton, New York, ISBN 0-393-31727-7, 251 pp.

Bøckman, O.C., Kaarstad, O., Lie, O.H., 1991. Landbruk og gjødsling. Mineralgjødsling i perspektiv (Agriculture and fertilisation. Mineral fertilisation in perspective). Norsk Hydro, Oslo, ISBN 82-90861-01-x, 248 pp.

Cederberg, C., 1998. Life Cycle Assessment of Milk Production. Report no. 643, The Swedish Institute for Food and Biotechnology, Gothenburg, ISBN 91-7290-189-6, 86 pp.

Cleveland, C.J., 1995. The direct and indirect use of fossil fuels and electricity in USA agriculture, 1910–1990. Agric. Ecosyst. Environ. 55, 111–121.

Cunney, M.B., 1982. Energy aspects of harvesting and drying. In: Robinson, D.W., Mollan, R.C. (Eds.), Energy Management in Agriculture, Vol. 11. Royal Dublin Society, Dublin, pp. 143–154.

Dalgaard, T., 2000. Farm types — how can they be used to structure, model and generalise farm data? In: Weidema, B.P., Meeusen, M.J.G. (Eds.), Agricultural Data for Life Cycle Assessments. Report 2.00.01, Agricultural Economics Research Institute, The Hague, The Netherlands, ISBN 90-5242-563-9, pp. 98–114.

Dalgaard, T., Halberg, N., Kristensen, I.S., 1998. Can organic farming help to reduce N-losses? Experiences from Denmark. Nutr. Cycling Agroecosyst. 52, 277–287.

Dalgaard, T., Halberg, N., Fenger, J., 1999. Fossil-based energy use and emission of greenhouse gasses in three scenarios for conversion to 100% organic farming in Denmark. Report no. 5, Danish Research Centre for Organic Farming (FØJO), Foulum, ISSN 1398-716-X, 57 pp.

Dalgaard, T., Halberg, N., Fenger, J., 2000. Fossil energy use and emissions of greenhouse gases — three scenarios for conversion to 100% organic farming in Denmark. In: van Lerland, E., Lansink, A.O., Schmieman, E. (Eds.), Proceedings of the International Conference on Sustainable Energy: New Challenges for Agriculture and Implications for Land Use, Wageningen, The Netherlands. Chapter 7.2.1, 11 pp.

Danish Farmers Unions (De Danske Landboforeninger), 1998. Landøkonomisk Oversigt (Agricultural Statistics). De Danske Landboforeninger, Copenhagen, ISSN 0107-7163, 127 pp.

de Boo, W., 1993. Environmental and Energy Aspects of Liquid Biofuels. Centrum voor energisparing en shone technologie, Delft, Holland.

Edwards, C.A., Grove, T.L., Harwood, R.R., Colfer, C.J.P., 1993. The role of agroecology and integrated farming systems in agricultural sustainability. Agric. Ecosyst. Environ. 46, 99–121.

Evans, L.T., 1998. Feeding the Ten Billion: Plants and Population Growth. Cambridge University Press, Cambridge, ISBN 0521640814.

Flavin, C., Dunn, S., 1998. Responding to the threat of climate change. In: Brown, L.R., Flavin, C.F., French, H. (Eds.), State of the World, Vol. 7. W.W. Norton, New York, ISBN 0-393-31727-7, pp. 113–130.

Fluck, R.C., 1992. Energy in Farm Production. Elsevier, Amsterdam, ISBN 0-444-88681-8, 367 pp.

Green, M., 1987. Energy in pesticide manufacture, distribution and use. In: Helsel, Z.R. (Ed.), Energy in Plant Nutrition and Pest Control, Vol. 7. Elsevier, Amsterdam, ISBN 0-444-42753-8, pp. 165–177.

Halberg, N., 1999. Indicators of resource use and environmental impact for use in a decision aid for Danish livestock farmers. Agric. Ecosyst. Environ. 76, 17–30.

Halberg, N., Kristensen, I.S., 1997. Expected crop yield loss when converting to organic dairy farming in Denmark. Biol. Agric. Hort. 14, 25–41.

Hitzhusen, F.J., 1993. Land degradation and sustainability of agricultural growth: some economic concepts and evidence from selected developing countries. Agric. Ecosyst. Environ. 46, 69–79.

Hjortshøj, A., Rasmussen, S., 1977. En kortlægning af den primære jordbrugssektors energiforbrug (Mapping the energy use of the primary sector). Report no. 7, Økonomisk Institut, Den Kongelige Veterinær-og Landbohøjskole, Copenhagen, 119 pp.

Hulscher, W.S., 1991. Basic energy concepts. In: Energy for Sustainable Rural Development Projects, Vol. 1. The United Nations Food and Agriculture Organisation (FAO), Rome, pp. 5–26.

International Federation of Institutes for Advanced Study (IFIAS), 1974. In: Slesser, M. (Ed.), Energy Analysis. Report no. 6, International Federation of Institutes for Advanced Study, Stockholm, 89 pp.

Intergovernmental Panel on Climate Change (IPCC), 1997. In: Houghton, J.T., et al. (Eds.), Greenhouse Gas Inventory Reference Manual, Vol. 3. IPCC Technical Support Unit, London.

Kuemmel, B., Langer, V., Magid, J., de Neergaard, A., Porter, J.R., 1998. Energetic, economic and ecological balances of a combined food and energy system. Biomass Bioenergy 15 (4/5), 407–416.

Leach, G., 1976. Energy and Food Production. IPC Science and Technology Press Limited, Guilford, Surrey, 151 pp.

Madsen, I., Petersen, D., 1981. Hjemkundskab Grundbog (Cooking — a primer). 9.udg, Aschehoug Forlag, Copenhagen, ISBN 87-11-02770-3, 181 pp.

McFate, K.L., 1983. Farm Energy Analysis. A Programe Aimed at Fostering a Team Approach for Implementing Wise Energy Management and Efficient Energy Use Practices on American Farms. The National Food and Energy Council, Columbia, MO.

Ministry of Environment and Energy, 1995. Danmarks Energifremtider (Danish energy futures). The Danish Energy Agency, Copenhagen, 214 pp.

Mudahar, M.S., Trignett, T.P., 1987. Fertiliser and energy use. In: Helsel, J.R. (Ed.), Energy in Plant Nutrition and Pest Control. Energy in World Agriculture, Vol. 2. Elsevier, Amsterdam, Chapter 1, 293 pp.

Mörschner, J., Bärbel, G., 1999. Direct and indirect energy use in arable farming — an example on winter wheat in Northern Germany. In: Weidema, B., Meeusen, M. (Eds.), Agricultural Data for Life Cycle Assessments, Proceedings of the Second European Invitational Expert Seminar on Life Cycle Assessments of Food Products, Den Haag, 25–26 January 1999. Institute for Product Development, Lyngby, Denmark.

Nielsen, V., 1985. Energiforbruget ved håndtering og behandling af grovfoder (Energy use for management and treatment of roughage). Report no. 40, Statens Jordbrugstekniske Forsøg, Horsens, Denmark, 35 pp.

Nielsen, V., 1987. Energiforbrug og arbejdsbehov ved direkte såning og traditionel jordbehandling (The need for energy and labour for direct sowing and conventional soil treatments). Report no. 77, Statens Jordbrugstekniske Forsøg, Horsens, Denmark, 35 pp.

Nielsen, V., 1989. Specific fuel consumption in European countries. Denmark. In: Pick, E., Noren, O., Nielsen, V. (Eds.), Energy Consumption and Input–Output Relations of Field Operations.

REUR Technical Series. Report no. 10, Food and Agriculture Organization of the United Nations, Rome, pp. 36–52.

Nielsen, V., 1991. Energiforbrug ved håndtering af græs (Energy use for management of grass). Report no. 47, Statens Jordbrugstekniske Forsøg, Horsens, Denamrk, 86 pp.

Nielsen, V., Sørensen, C.G., 1994. Drift. Et program til beregning af arbejdsbehov, arbejdskapacitet, arbejdsbudget og arbejdsprofil (A programme to calculate the need for labour). Report no. 53, Statens Jordbrugstekninske Forsøg, Horsens, Denmark, 124 pp.

Odum, H.T., 1971. Fundamentals of Ecology, 3rd Edition. Saunders, Philadelphia.

Opschoor, H., Reijnders, L., 1991. Towards sustainable development of indicators. In: Verbruggen, H., Kuik, O. (Eds.), Search of Indicators of Sustainable Development, Vol. 2. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 7–28.

Pick, E., 1984. Rationalisation of energy demands in field operations. In: Nielsen, V. (Ed.), Energiforbruget ved håndtering og behandling af grovfoder (udredningsprojekt), Proceedings of the FAO-Meeting, Bruxelles, February 1984. Report no. 40, Statens Jordbrugstekniske Forsøg, Horsens, Denmark, 35 pp.

Pick, E., Netik, O., 1989. Specific fuel consumption in European countries. Czechoslovakia. In: Pick, E., Noren, O., Nielsen, V. (Eds.), Energy Consumption and Input–Output Relations of Field Operations. REUR Tecnical Series. Report no.10, Food and Agriculture Organization of the United Nations, Rome.

Pimentel, D., 1980. Handbook of Energy Utilization in Agriculture. CRC Press, Boca Roton, FL, ISBN 0-8493-2661-3, 475 pp.

Pimentel, D., Pimentel, M., 1996. Food, Energy and Society. ISBN 08-70-81386-2.

Pimentel, D., Beradi, G., Fast, S., 1983. Energy efficiency of farming systems: organic and conventional agriculture. Agric. Ecosyst. Environ. 9, 359–372.

Pimentel, D., Hurd, L.E., Bellotti, A.C., Forster, M.J., Oka, I.N., Sholes, O.D., Whitman, R.J., 1973. Food production and the energy crisis. Science 182 (4111), 443–449.

Pimentel, D., Brown, N., Vecchio, F., La Capra, V., Hausman, S., Lee, O., Diaz, A., Williams, J., Cooper, S., Newburger, E., 1992. J. Agric. Environ. Ethics 5 (2), 113–146.

Pinstrup-Andersen, P., 1999. Towards Ecologically Sustainable World Food Production, Vol. 22. UNEP Industry and Environment, United Nations Environment Programme, Paris, pp. 10–13.

Plentinger, M.C., Penning de Vries, F.W.T., 1996. Register of agro-ecosystems Models. Report no. II, CAMASE (concerned action for the development and testing of quantitative methods for research on agricultural systems and the environment), Wageningen, Holland, 411 pp.

Refsgaard, K., Halberg, N., Kristensen, E.S., 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agric. Syst. 57 (4), 599–630.

Sensi, A., 1999. Agriculture and climate change. In: Agriculture, Environment, Rural Development: Facts and Figures — A Challenge for Agriculture. EU Comission, DG VI, DG XI, and EUROSTAT, http://europa.eu.int/comm/dg06/envir/report/en/index.htm.

Sonesson, U., 1993. Energianalyser av biobränslen från Höstvete, Raps och Salix (Energy analysis of biofuels from Winter wheat, Rape seed and Salix). Report no. 174, Sveriges Lantbruksuniversitet, Uppsala, Sweden, 54 pp.

Soddy, F., 1933. Welth, Virtual Welth and Department. Allen & Unwin, London, 57 pp.

Statistics Denmark, 1996. Danish Agricultural Statistics. ISBN 87-501-1034-9, 310 pp.

Stout, B.A., Myers, C., Schwab, G., et al. 1982. Energy management in US production agriculture. In: Robinson, D.W., Mollan, R.C. (Eds.), Energy Management and Agriculture, Vol. 5. Royal Dublin Society, Dublin, pp. 67–84.

Strudsholm, F., Nielsen, E.S., Flye, J.C., 1997. Fodermiddeltabel 1997 (fodder stuff table 1997), Vol. 69. Danish Extension Service, Skejby, pp. 1–53.

The Danish Energy Agency, 1997. Energistatistik 1996 (Energy Statistics 1996). ISBN 87-7844-065-3, 36 pp.

The Danish Producers of Electricity (De Danske Elværker). 1994. Energirådgivning — Landbrug (Energy advise — agriculture). De Danske Elværkers Forening, Frederiksberg, Copenhagen, ISBN 87-87071-47-9, 225 pp.

The European Commission, 1997. Harmonisation of environmental life cycle assessment for agriculture. In: Audsley, E. (Ed.), Final Report Concerted Action AIR3-CT94-2028. European Commission DG VI Agriculture, Brussels.

Tsatsarelis, C.A., 1993. Energy inputs and outputs for soft winter wheat production in Greece. Agric. Ecosyst. Environ. 43, 109–118.

Uhlin, H., 1998. Why energy productivity is increasing: an I–O analysis of Swedish agriculture. Agric. Ecosyst. Environ. 56 (4), 443–465.

Vester, J., 1995. Energibalancer (Energy balances). In: Olesen, J.E., Vester, J. (Eds.), Næringsstofbalancer og energiforbrug i økologisk jordbrug-fokus på kvægbedrifter og planteavl. Report no. 8, Statens Planteavlsforsøg, Lyngby, pp. 106–116.

Vitlox, M., Pletinckx, 1989. Specific fuel consumption in European countries: Belgium. In: Pick, E., Noren, O., Nielsen, V. (Eds.), Energy Consumption and Input–Output Relations of Field Operations. REUR Technical Series. Report no. 10, Food and Agriculture Organization of the United Nations, Rome, pp. 12–17.

Weidema, B., Meeusen, M., 1999. Agricultural data for life cycle assessments. In: Proceedings of the Second European Invitational Expert Seminar on Life Cycle Assessments of Food Products, Den Haag, 25–26 January 1999. Institute for Product Development, Lyngby, Denmark.

White, R.G., 1974. Fuel requirements for selected farming operations. Bulletin E-780, Michigan State University, MI, USA.