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On-farm greenhouse gas emissions associated with the cultivation of two new bioenergy crops in the UK

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ABSTRACT

Before using novel energy crops to produce bioenergy, feasibility studies should be completed to determine their effect on net greenhouse gas emissions. The current study developed a model to study the greenhouse gas emissions associated with the cultivation of two novel bioenergy crops: *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., using Intergovernmental Panel on Climate Change (IPCC) guidelines. The establishment and cultivation of *Sida hermaphrodita* and *Silphium perfoliatum* were compared with an arable rotation, short rotation coppice (SRC) and Miscanthus. Under the assumptions specified in the current study, including annual fertilisation and a high root: shoot ratio for Sida, the cultivation of *Sida hermaphrodita* and *Silphium perfoliatum* resulted in a mean net emission of 3.0 Mg CO_2eq $ha^{-1}y^{-1}$ and mean net sequestration of 0.6 Mg CO_2eq $ha^{-1}y^{-1}$ respectively over a 16 year rotation. This compared to predicted mean net emissions of 4.2 Mg CO_2eq $ha^{-1}y^{-1}$ for an arable rotation, and intermediate values for the SRC and Miscanthus crop (1.0 and 2.2 Mg CO_2eq $ha^{-1}y^{-1}$, respectively).

1. Introduction

Climate change is such a critical issue that 195 countries signed the Paris Agreement and committed themselves to limiting global warming to less than 2°C compared to pre-industrial revolution levels [51]. In response, the United Kingdom, alongside other countries, set the target of achieving zero net emissions of greenhouse gases (GHG) by 2050 [50]. Achieving net zero GHG emissions requires careful consideration of the most appropriate sources of renewable low-carbon energy. One form of renewable energy that has a key role to play in the agricultural sector is bioenergy.

There are several factors influencing GHG emissions during the cultivation of the majority of crops [24]. First of all, all operations for crop production that require using a tractor will be consuming diesel fuel, which combustion in the engine of the tractor will be a direct source of GHG emissions, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In a cropland set up, there are several carbon pools that can act either as source or a sink of carbon depending on the inputs and outputs: biomass pool, managed soils pool, and dead organic matter pool. Thanks to the photosynthesis process, all plants store carbon in their systems, converting light, nutrients, water, and CO_2 into glucose and oxygen. In terms of calculating GHG emissions over a set number of years, annual crops are not included in long term calculations of the biomass pool because they are harvested annually and dye completely shortly after. However, perennial crops remain alive for extended periods of time, some even over 20 years, and their alive biomass remains an active carbon stock during their lifetime, dependant on the plant species, cultivation practices and climatic conditions. Agricultural soils are another carbon stock, which content varies with management practices and climactic conditions. Dead organic matter also contributes to the overall carbon balance of cropland through decomposition of dead wood and litter accumulated on the soil surface. Lastly, there are several sources of nitrous oxide emissions that naturally occur in soils that need to be accounted for, traditionally divided into direct and indirect N_2O emission. Direct N_2O emissions are greatly influenced by the availability of inorganic N in the soil, directly dependant on the amounts of fertiliser used. Indirect N_2O emissions originate from atmospheric deposition (including previous volatilisation from managed soils) and N leaching or run off [25].

When it comes to calculating GHG emissions from a farm, there are many carbon footprint calculators currently available in the UK market using a variety of methodologies and models: free to use straight away, such as the Carbon Footprint Decision Tool from AHDB for oilseed rape and cereals [5]; free to use after registration, like the Farm Carbon Toolkit for a wide range of farming systems [17] and the Cool Farm Tool for perennial systems [9]; free use with limited features/assessments, such as the Farm Carbon Calculator [4], also suited for a wide range of farming systems; with monthly/annual cost associated, like Sandy [49].

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Bioenergy in the agricultural sector can be produced from food crops, animal feed, trees and perennial bioenergy crops. The SidaTim European Joint Project [1] identified the crops *Sida hermaphrodita* and *Silphium perfoliatum*, referred as Sida and Silphium from here onwards, as two potential perennial bioenergy crops which could be grown across Europe. Sida and Silphium are tall perennial grasses (up to 3m) that can produce mature dry matter (DM) yields ranging between 5-20 t DM $ha^{-1}y^{-1}$ and 12-25 t DM $ha^{-1}y^{-1}$, respectively, when harvested in late summer for green biomass production for anaerobic digestion or late winter for solid fuel production for combustion, remaining productive for more than 15 years [10]. A review of the available literature [10] showed that environmental benefits of the two crops included phytoremediation, phytostabilization, enhanced biodiversity, pollination and soil health regulation. However, considering the current climate emergency and before fully endorsing the cultivation of Sida and Silphium, the GHG emissions associated with their cultivation need to be considered.

At the time this study was undertaken and to the authors knowledge, there was no published research in English that studied the GHG emissions from cultivating Sida or Silphium. Hence, the aim of the work described herein was to fill this gap and present the results from a GHG emissions accounting model that was developed following the guidelines of the Intergovernmental Panel on Climate Change (IPCC).

2. Material and methods

A GHG emissions accounting model was developed to compare the cultivation of a rotation of five arable crops, and four bioenergy crops, including Sida and Silphium, in the United Kingdom. The systems included in the assessment were (a) an arable rotation comprising wheat, sugar beet, forage maize, oilseed rape (OSR) and oats, (b) willow short rotation coppice (SRC), (c) Miscanthus, (d) Sida and (e) Silphium. For further information about the selected bioenergy species please refer to the corresponding crop fact sheets for SRC [39], Miscanthus [40], Sida [38] and Silphium (Donau [14]). The study followed the IPCC guidelines for national greenhouse gas inventories [24,29] for the Agriculture, Forestry and Other Land Use (AFOLU) sector. This method accounts for carbon stock variations as CO_2 emissions and removals, along with non-CO_2 emissions. The selected functional units for mass and area were 1 t of DM and 1 ha.

2.1. Land of study

It was assumed that each crop was cultivated on a sandy soil in Bedfordshire (where an experimental field was established parallel to this study) in the United Kingdom, characterised by a cool temperate climate. The study compared the GHG emissions produced from the selected agricultural systems over a rotation of 16 years, as standard for this kind of studies. No land-use changes were incorporated in the analysis, because it was considered that the land-use category is cropland remaining cropland (CL remaining CL).

2.2. Definition of system boundaries and key categories

The farm-gate was selected as the system boundary (Fig. 1). The GHG fluxes considered covered land-use and crop production operations, CO_2 emissions or removals by sinks from various carbon pools, and other GHG gases (N_2O, CH_4). Default tier 1 methods and data values indicated in the IPCC guidelines were normally used unless otherwise stated. Country-specific emission factors (EF) for the United Kingdom were used to calculate the emissions from fuel combustion activities.

The study included emissions derived from agricultural activity such as emissions from fossil fuels used during agricultural operations, carbon stock changes, and N_2O emissions from managed soils (Table 1). The GHG emissions and removals during the production of the planting material, manufacturing of machinery or manufacturing of agrochemical products, and emissions resulted beyond the farm-gate were out of scope.

Table 1
Emissions associated with the cultivation and production of the crops included in the model.

Emissions	IPCC Code	CO_2	CH_4	N_2O
1. Emissions from fuel combustion activities	1A4	x	x	x
2. Carbon stock change in biomass pool	3B2a	x		
3. Carbon stock change in mineral soil	3B2a	x		
4. Carbon stock change in litter pool	-	x		
5. Direct N_2O emissions from managed soils	3C4			x
6. Indirect N_2O emissions from managed soils	3C5			x

2.3. Emissions from fuel combustion activities

All the agricultural operations required for the establishment, maintenance and harvest of crops involve the use of tractors (and other self-propelled machines), powered by diesel. Diesel combustion produces three main GHG to the atmosphere: CO_2, CH_4, and N_2O. These emissions were calculated multiplying the quantity of the fuel consumed ($Fuel_j$) with the corresponding emission factor (EF_j) as outlined by the guidelines [23] (Equation 1) (Appendix, A1.).

$$\textbf{Emissions} = \sum_j \left(Fuel_j * EF_j \right) \qquad \text{(Equation 1)}$$

The emission factors (*EF*j) for carbon dioxide, methane, and nitrous oxide from diesel, (0.25677, 0.00003, and 0.00343 kg $CO_2/CH_4/N_2O$ kWh^{-1}, respectively), were obtained from the UK Government GHG Conversion Factors for Company Reporting database [7]. The quantity of diesel consumption per unit area (f_e; l ha^{-1}) was calculated using Equation 2,

$$f_e = \left(Sfc * P * q_A * n \right) / d_f \qquad \text{(Equation 2)}$$

where *Sfc* is the specific fuel consumption (kg kWh^{-1}), P is the rated power of the tractor and equipment (kW), q_A is the work rate (h ha^{-1}), n is the number of passes, and d_f is the density of the fuel (kg l^{-1}). The rated power, the work rate, and the number of passes were derived from Williams *et al.*, [53]. The specific fuel consumption (220 g diesel kWh^{-1}) was derived from Handler and Nadlinger [18] and the fuel density (0.854 kg l^{-1}) from BEIS and DEFRA [7].

After the nitrous oxide and methane emissions were obtained (kg ha^{-1}), they were multiplied by the corresponding Greenhouse Warming Potential (GWP) [35] to convert them into kg CO_2eq ha^{-1}, i.e. 298 and 30 for N_2O and CH_4 respectively.

2.4. Carbon stock change estimation

Annual emissions and removals of CO_2 (carbon stock changes) can be estimated as the sum of changes in all land-use categories. Carbon stock changes were derived from the variations occurring in the biomass (above and below ground), the soil, and the litter carbon pools which were summed. In the case of arable crops, dead organic matter consists of litter plus residual roots. In a long-term arable rotation, the supply of crop residues and tillage intensity can be regarded as approximately constant for each crop in the rotation. In a long-term perennial cropping system, such as Sida, Silphium, SRC and Miscanthus, tillage is limited to the establishment year and weeding in the first few years. Crop residues in perennial systems will vary depending on the species and time of the harvest.

2.4.1. Biomass pools

The net accumulation of carbon in the biomass pool for arable crops was assumed to be zero, because the increase in biomass stocks for arable crops in a year are considered to be equal to the losses from harvest and mortality in the same year [29]. Therefore, changes in the

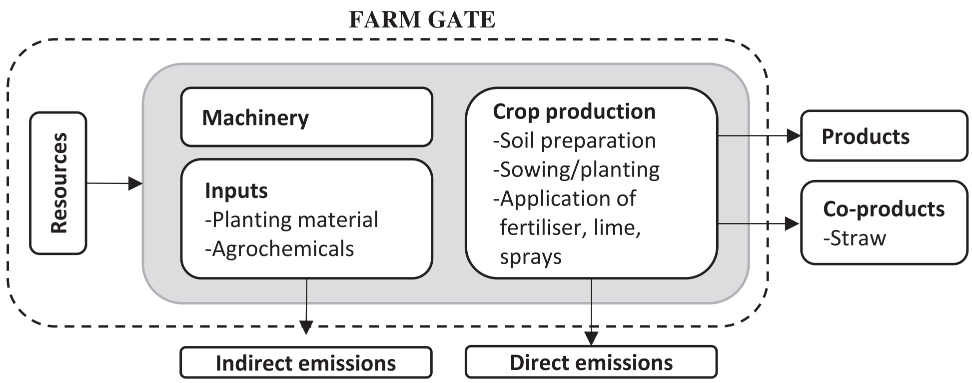

Fig. 1. System boundaries diagram for the analysis of the indirect and direct greenhouse gas emissions for the different biomass crops, based on FAO [16].

Table 2
Assumed yields and yield profiles of the SRC, Miscanthus, Sida, and Silphium crops.

Year	Harvested dry matter yield (t $ha^{-1}y^{-1}$)			
	SRC *	Miscanthus	Sida	Silphium
1	-	0.60	2.05	0.00 [1]
2	-	3.93	8.27	9.93
3	-	11.10	10.93	14.70
4	30.00	12.54	11.62	15.73
5	-	12.54	11.62	16.30

* SRC harvests: first harvest on year 4, afterwards every 3 years.
[1] It is considered that perennial crops such as Sida and Silphium reach maturity on the 4th year of cultivation, which becomes year 5 for Silphium since the 1st year this crop only grows a rosette.

Table 3
Factors used for the calculation of soil organic carbon (SOC) stocks for arable and energy crops at the beginning ($SOC_{0\text{-}T}$) and the end (SOC_0) of the inventory period for a mineral soil (see Appendix, A2.3.).

Factor	$SOC_{0\text{-}T}$		SOC_0	
	Arable	Energy	Arable	Energy
F_{LU}	0.70	0.70	0.70	0.72
F_{MG}	1.0	1.0	1.0	1.04
F_I	1.0	1.0	1.0	1.11
SOC_{ref}	76.0	76.0	76.0	76.0

where: F_{LU} = stock change factor for land-use systems for a particular land-use (); F_{MG} = stock change factor for management regime (); F_I = stock change factor for input of organic matter (); SOCref = reference carbon stock (t C ha^{-1})

carbon stock pool of biomass were only calculated for perennial (energy) crops, using the IPCCC guidelines (Appendix, A1.).

Whenever the IPCC guidelines provided specific data on the studied crops, those data were used as model input. Yield data (Table 2) of energy crops until they reached maturity were extracted from ABC Ltd [2] for SRC and Cumplido-Marin *et al.* [11] for Miscanthus, Sida and Silphium. The ratios of below ground to above ground biomass (R) were extracted from literature sources and experimental data, corresponding to 0.13 [20], 0.39 [33], 2.35 (experimental data) and 0.52 [44] for SRC, Miscanthus, Sida and Silphium respectively. The root to shoot ratio of Sida was calculated from 1 year old plants within a field trial in Bedfordshire, England as part of the SidaTim research project, where Sida roots represented approximately 70% of total plant dry biomass. It was assumed that the underground biomass of Sida increases at a constant rate until year 4, when it reaches an equilibrium, and at a rate of 6.5% from year 5 onwards (based on results from Pacaldo *et al.* [41], 46% increase over 7 years). The root to shoot ratio could not be calculated for Silphium due its slow development during the first year. The whole dataset of calculations is included in Appendix, A2. The carbon fraction (CF) of the biomass was extracted from the 2019 Refinement of the IPCC guidelines [26,27,29], being 0.50, 0.37 and 0.47 for dead wood/biomass, litter and herbaceous biomass respectively.

Assumed root growth rates were derived from literature sources and experimental data, corresponding to 0.7 t DM $ha^{-1}y^{-1}$ [34], 1.50 t DM $ha^{-1}y^{-1}$ [8], 1.71 t DM $ha^{-1}y^{-1}$ (experimental data) and 0.53 t DM $ha^{-1}y^{-1}$ [44] for SRC, Miscanthus, Sida and Silphium respectively.

2.4.2. Soil pool

Calculation of the carbon dioxide fluxes from the mineral soil pool was done by classifying the crops into arable and energy crops. The factors and reference SOC levels (SOC_{ref}) for the calculation of SOC stock at the beginning ($SOC_{0\text{-}T}$) and the end of the inventory period (SOC_0) are summarised in Table 3. These parameters were extracted from Chapter 2 and Chapter 5 of the IPCC guidelines [28,29]. The inventory period was assumed to be 16 years to match with a typical rotation of the energy crops. The SOC stock of energy crops at the beginning of the inventory ($SOC_{0\text{-}T}$) period was set to be equal to the SOC stock of arable crops at the end of the inventory period (SOC_0).

2.4.3. Litter pool

The IPPC stock-difference method was used for the estimation of changes in the litter pool for energy crops (Appendix, A1.). The emissions were calculated from the establishment year until the crops reach maturity, using the yields provided in Table 2. Litter data for SRC and Miscanthus were extracted from the literature, respectively 1.85 t DM $ha^{-1}y^{-1}$ [19] and 30% (29-42%) of the production [32]. Sida was considered to be harvested at the end of winter for the production of solid fuel, its fractional rate of litter production for assumed to be the same as Miscanthus, i.e. 36% of the harvested yield. The carbon fraction (CF) of litter was fixed at 0.37. The litter stock at the end of the inventory period was estimated to be 0 for Silphium due to the fact that it is harvested for green biomass, and hence leaf abscission is minimal. The complete set of calculations is included in Appendix, A2.

2.5. N_2O emissions

Direct emissions of nitrous oxide can be derived from nitrification and denitrification processes (Fig. 2). These processes can be increased by addition of N fertilisers and crop residues and through N mineralisation which occurs after cultivation of mineral soils [25]. Indirect N_2O emissions can originate from volatilisation of ammonia and nitrogen oxides, combustion of fossil fuels and from nitrate leaching and run off from managed soils [25]. Converting N_2O-N emissions to N_2O emissions was done using by multiplying by 44/28.

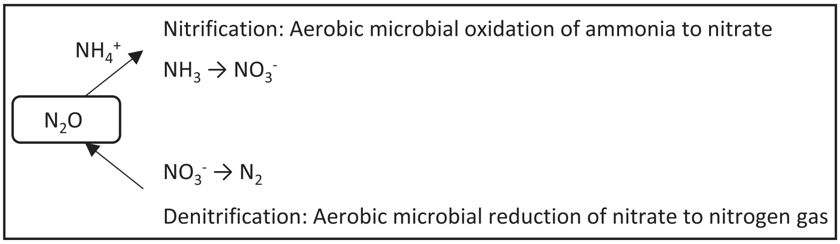

Fig. 2. N_2O emissions simplified diagram of direct emissions

Table 4
Activity data and coefficients used to derive above and below ground estimates of crop residues.

Crop	$Crop_{(T)}$ (kg DM ha^{-1})	F_{SN} (kg ha^{-1})	$AGR_{(T)}$ (kg DM y^{-1})	$R_{AG(T)}$ ()	$RS_{(T)}$ ()	DRY (%)	$Frac_{rem(T)}$ ()	$Frac_{renT)}$ ()	$N_{AG(T)}$ ()	$N_{BG(T)}$ ()
Wheat	7,390	190	3,900	1.3	0.23	0.89	0.0	1.0	0.006	0.009
Oats	5,610	130	3,500	1.3	0.25	0.89	0.0	1.0	0.007	0.008
OSR	3,150	190	2,600	0.3	0.54	0.90	0.0	1.0	0.015	0.012
Sugar beet	16,940	156	500	0.4	0.20	0.22	0.0	1.0	0.019	0.014
Forage maize	10,440	150	3,310	1.0	0.22	0.87	0.0	1.0	0.006	0.007
$SRC_{y1\text{-}y4}$	30,000	90	1,850	0.3	0.8	-	0.0	0.25	0.015	0.012
$SRC_{y5\text{-}onwards}$	30,000	90	1,850	0.3	0.8	-	0.0	0.33	0.015	0.012
Miscanthus	12,500	84	4,450	0.3	0.8	-	0.0	1.0	0.015	0.012
Sida	11,600	100	4,120	0.3	0.8	-	0.0	1.0	0.015	0.012
Silphium	16,300	120	5,790	0.3	0.8	-	0.0	1.0	0.015	0.012

where: $Crop_{(T)}$ = harvested annual dry matter yield for crop T (kg DM ha^{-1}) = Fresh yield * dry matter (%); F_{SN} = annual amount of synthetic fertiliser N applied to soils (kg N $ha^{-1}y^{-1}$); $AGR_{(T)}$ = annual above-ground crop residue for crop T (kg DM y^{-1}); $R_{AG(T)}$ = ratio of above-ground residues dry matter (AGDM(T)) to harvested yield; $RS_{(T)}$ = ratio of below-ground residue to harvested yield of crop T; DRY = percentage dry matter; $Frac_{rem(T)} = Frac_{remove(T)}$ = fraction of above-ground residues crop T removed annually, if not available assume no removal; $Frac_{ren(T)} = Frac_{renew(T)}$ = fraction of total area under crop T renewed annually. Annual crops Fracrenew = 1; $N_{AG(T)}$ = N content of above-ground residues for crop T (kg N per kg DM); $N_{BG(T)}$ = N content of below-ground residues for crop T (kg N per kg DM).

2.5.1. Direct N_2O emissions

Direct N_2O emissions derived from the application of N fertilisers were calculated following the IPCC methodology (Appendix, A1.). Crops yields ($Crop_{(T)}$) and synthetic nitrogen fertiliser doses (F_{SN}) for arable crops were obtained from the John Nix Pocket Book for Farm Management [3]; from the Agricultural Budgeting and Costing book [2] for SRC and Miscanthus; and from Table 2 for Sida and Silphium.

Annual above ground crop residues ($AGR_{(T)}$) for wheat, oats and OSR were obtained from DEFRA [12]; from Torma *et al.* [48] for sugar beet and forage maize; litter data of mature energy crops reference in the previous section were used for SRC, Miscanthus, Sida and Silphium. It was considered that the residues of all crops were not removed ($Frac_{remove(T)} = 0$) and that all the cropped area was renewed annually for all crops ($Frac_{renew(T)} = 1.0$) but for SRC ($Frac_{renew(T)\ y1\text{-}y4} = 0.25$ and $Frac_{renew(T)\ y5\text{-}onwards} = 0.33$).

The ratio of below-ground residue to harvested yield ($RS_{(T)}$), the ratio of above-ground residues dry matter to harvested yield ($R_{AG(T)}$), dry matter content of arable crops, nitrogen content of above and below ground residues ($N_{AG(T)}$, $N_{BG(T)}$) were extracted from the corresponding volume of the guidelines [29]. Because no land use change was assumed, the annual amount of N in mineral soils that is mineralised in association with land use changes (F_{SOM}) was considered to be zero. A summary of the data applied in the model for the different crops is presented in Table 4, with all calculations shown in Appendix, A2.

2.5.2. Indirect N_2O emissions

Indirect N_2O emissions included were from N volatilisation (NH_3, NO_x) and atmospheric deposition (NH_3, NO_x, NH_4^+, NO_3^-) on soil and water surfaces, the application of synthetic fertilisers (F_{SN}), the nitrogen in crop residues (F_{CR}) and N mineralisation linked to soil organic matter loss as a result of management of mineral soils (Fig. 3). Indirect N_2O emissions were calculated following IPCC guidelines (Appendix, A1.).

The parameters used for the calculation of nitrous oxide emissions derived from atmospheric deposition and from leaching/run off were extracted from the IPCC guidelines [29]. The fraction of synthetic N fertiliser that volatilises as NH_3 and NO_x ($Frac_{GASF}$) and the emission factor for N_2O emission from atmospheric deposition of N on soils and water surfaces (EF_4) were set respectively at 0.11 and 0.014 for all crops. The fraction of all N additions to managed soils that is lost through leaching and runoff ($Frac_{LEACH\text{-}H}$) and the emission factor for N_2O emission from N leaching and runoff were set respectively at 0.24 and 0.011. The amount of N in crop residues (above and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually (F_{CR}) was fixed at 0 to avoid double-counting (already accounted for in the emissions derived from litter).

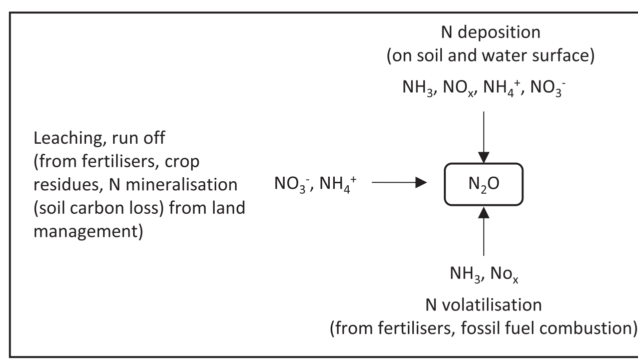

Fig. 3. Indirect N_2O emissions included in the study

3. Results

The amounts of CO_2, CH_4 and N_2O derived from diesel consumption during agricultural operations was estimated annually for each crop (Table 5). For energy crops, years were differentiated by establishment,

Table 5
Annual emissions derived from diesel consumption during agricultural operations (see Appendix, A2., A2.2.).

Crop and year	Annual emission (kg CO_2eq $ha^{-1}y^{-1}$)			
	CO_2	CH_4	N_2O	Total
Wheat	493	1.73	1750	2240
Oats	493	1.73	1750	2240
OSR	254	0.89	899	1150
Sugar beet	1240	4.33	4380	5620
Forage maize	494	1.73	1750	2250
SRC (establishment)	423	1.48	1500	1920
SRC (recurring no harvest)	82	0.287	290	372
SRC (recurring harvest years)	232	0.813	822	1060
Miscanthus (establishment)	423	1.48	1500	1920
Miscanthus (recurring)	129	0.450	455	585
Sida (establishment)	495	1.73	1750	2250
Sida (recurring)	176	0.617	624	801
Silphium (establishment)	382	1.34	1350	1740
Silphium (recurring)	176	0.617	624	801

Table 6
Predicted carbon stock changes in the below ground biomass pool (mean annual emissions over 16 year period).

Crop	Annual CO_2 emissions (kg CO_2 $ha^{-1}y^{-1}$)
SRC	-1446
Miscanthus	-3591
Sida*	-2944
Silphium	-1371

* Weighted average of emissions in years 1-4 and year5-onwards.

Table 7
Carbon dioxide emissions derived from litter production of energy crops.

	Carbon stock change in litter pool (kg CO_2 $ha^{-1}y^{-1}$)			
	SRC	Miscanthus	Sida	Silphium
Year 1	2510	289	986	0
Year 2	2510	1890	3980	0
Year 3	2510	5346	5260	0
Year 4 and onwards	2510	6040	5590	0

recurring no harvest/harvest for SRC, or simply recurring annual harvest in the case of Miscanthus, Sida and Silphium.

Because almost all above-ground biomass of crops is removed every harvest, the predicted carbon stock change for SRC, Miscanthus, Sida and Silphium in the above-ground biomass pool during their rotation was zero. The below-ground biomass produced by SRC, Miscanthus, Sida (year1-year5/year5-onwards) and Silphium resulted in the sequestration of 1450, 3590, 9850/640, 1370 kg CO_2 ha^{-1} annually (Table 6), with the initial high Sida values due to the high root: biomass ratio. Growing SRC, Miscanthus, Sida and Silphium were predicted to retain on average approximately 2280 kg CO_2 ha^{-1} in the soil pool per year (Appendix, A2., A2.3.). Carbon dioxide emissions derived from litter production of energy crops are summarised in Table 7.

Annual direct and indirect nitrous oxide emissions from managed soils are summarised in Table 8. The results from the 16 years simulation under different cropping systems were calculated and converted into CO_2eq ha^{-1}; all summarised in Fig. 4.

Our model calculated that the arable rotation and Sida emitted 9.40 and 2.45 Mg CO_2 ha^{-1} over the 16 years, equivalent to 0.588 and 0.153 Mg CO_2 $ha^{-1}y^{-1}$ respectively. The perennial systems of SRC, Miscanthus, and Silphium removed carbon dioxide from the atmosphere, fixing a total of 17.3, 5.61, and 55.5 Mg CO_2 ha^{-1} over 16 years, equivalent to 1.08, 0.350 and 3.47 t of CO_2 $ha^{-1}y^{-1}$ respectively. Methane emissions during the 16 years of cultivation from all five systems were minimal, ranging from 0.0330 (arable rotation), 0.0237 (SRC), 0.0110 (Sida), 0.0106 (Silphium), to 0.00824 (Miscanthus) Mg CO_2eq ha^{-1}. Nitrous oxide emissions from all studied systems during their lifetime in order from highest to lowest were (in Mg CO_2eq ha^{-1}): arable rotation (58.6); Silphium (45.8); Sida (44.2); Miscanthus (41.3), and SRC (34.0). Overall predicted emissions in terms of Mg CO_2eq $ha^{-1}y^{-1}$ in order from highest to lowest were positive for the arable rotation, Sida, Miscanthus, SRC and (4.25, 2.92, 2.23, 1.05), and negative for Silphium (-0.603).

Table 8
Predicted annual direct and indirect N_2O emissions from the soil for each crop.

Crop	Direct N_2O emissions (kg CO_2eq $ha^{-1}y^{-1}$)	Indirect N_2O emissions (kg CO_2eq $ha^{-1}y^{-1}$)
Wheat	1630	122
Oats	1180	83.4
OSR	1670	122
Sugar beet	1520	100
Forage maize	1320	96.2
SRC*	1540	57.7
Miscanthus	2010	53.9
Sida	2010	64.1
Silphium	2120	77.0

* Weighted average of emissions in years 1-4 and year5-onwards.

4. Discussion

A key point to consider in this study is the duration of carbon sequestration. The current study considered a growth period of 16 years, which some authors could argue is too short a period to reach a new equilibrium, as indicated by BSI [42]. A practical field assessment should analyse the initial land use soil equilibrium state, because this affects the potential increase on SOC. For the duration of the experiment, soil texture, climate, and the rate of carbon inputs should be taken into account.

It is important to note that the end of use of the biomass has a great impact on the result, as can be observed for Silphium where the green biomass is harvested in late summer, and therefore there is no litter production and no increase in carbon dioxide emissions from the litter pool for this crop.

The results demonstrate that the net GHG balance of the five systems are primarily determined by the assumed rate of carbon sequestration, the nitrous oxide emissions associated with fertilizer and diesel use, and the end use of the biomass. If the fate of biomass from Sida was to produce biogas instead of solid fuel, its overall emissions balance would change drastically from being a source of emissions to being a sink (-2.27 Mg CO_2eq $ha^{-1}y^{-1}$). The results obtained from the model indicate that the predicted annual direct N_2O emissions from the soil for Miscanthus, Sida and Silphium are higher than the predicted annual direct N_2O emissions from the soil for SRC and the arable crops. This can be explained by the large amounts of residue-N calculated for Miscanthus, Sida, and Silphium crops as well as to the annual application of fertilizer-N.

Don *et al.* [13] reviewed measured nitrous oxide emissions of perennial systems compared with arable systems obtained by various authors. From five European trials, they recorded nitrous oxide emissions between 0.10-0.50 Mg CO_2eq $ha^{-1}y^{-1}$ for Miscanthus, between 0.05-0.90 Mg CO_2eq $ha^{-1}y^{-1}$ for poplar, and between 0.00-0.50 Mg CO_2eq $ha^{-1}y^{-1}$ for willow. These values are less that those obtained in the cur-

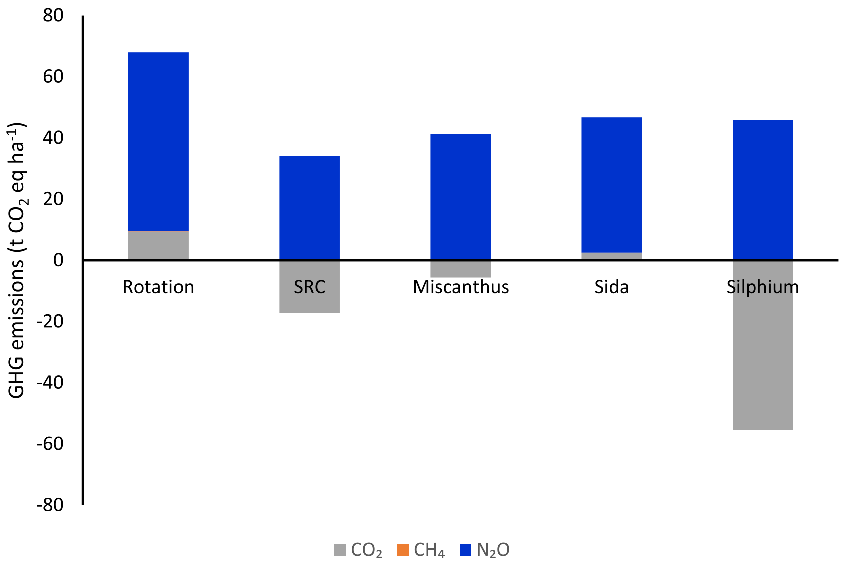

Fig. 4. Predicted cumulative net GHG emissions per GHG type produced during 16 years rotation.

Table 9
Summary of the contributions of annual GHG fluxes associated with an arable rotation, SRC, Miscanthus, Sida, and Silphium crops.

	Predicted net sequestration or emissions [a] ($Mg\ CO_2eq\ ha^{-1}y^{-1}$)					
	CO_2 emissions	CH_4 emissions	N_2O emissions from fca*	N_2O from other sources	Total N_2O emissions	Net emissions
Arable rotation	0.588	2.08E-03	2.08	1.58	3.66	4.25
SRC	-1.08	1.48E-03	0.531	1.59	2.13	1.05
Miscanthus	-0.350	5.15E-04	0.520	2.06	2.58	2.23
Sida	0.153	6.87E-04	0.694	2.07	2.76	2.92
Silphium	-3.47	6.63E-04	0.669	2.19	2.86	-0.603

[a] Positive values indicate emissions, whilst negative values indicate sequestration
* fca= fuel combustion activities

rent study of 2.13 and 2.58 $Mg\ CO_2eq\ ha^{-1}y^{-1}$ for SRC and Miscanthus, respectively.

During a four-year experiment, Hellebrand *et al.* [21] recorded the nitrous oxide emissions of SRC and annual crops under different fertilisation regimes in Germany, observing significantly lower emissions from SRC compared to annual crops in all cases. For the doses of 0, 75, and 150 kg N ha^{-1} they recorded nitrous oxide emissions of 0.50-0.57, 0.94-1.14, and 1.15-1.99 kg NO_2-N $ha^{-1}y^{-1}$. If we compare those results with the results from the current study, where we calculated that 3.69 kg N_2O-N $ha^{-1}y^{-1}$ were produced by the SRC system assuming a fertilisation rate of 90 kg N ha^{-1}, the results from the current study are substantially higher. This indicates that the model is most likely overestimating nitrous oxide emissions, potentially being substantially lower in reality. If we used one of the values given by Hellebrand *et al.* [21] as input for our model, 1.99 kg N_2O-N $ha^{-1}y^{-1}$ for SRC, this would result in overall N_2O emissions to be 1.42 $Mg\ CO_2eq\ ha^{-1}y^{-1}$ (as opposed to 2.13 $Mg\ CO_2eq\ ha^{-1}y^{-1}$).

In their 2.5 years experimental field in Lincolnshire (UK), Drewer *et al.* [15] demonstrated that the cultivation of Miscanthus and SRC (with no fertilisation) produced about five times less nitrous oxide emissions than arable rotations, observing no significant differences between SRC and Miscanthus. They reported that SRC and Miscanthus produce respectively 0 and 0.2 $Mg\ CO_2eq\ ha^{-1}y^{-1}$ of nitrous oxide emissions (with no fertilisation), compared to 0.4-1.3 $Mg\ CO_2eq\ ha^{-1}y^{-1}$ from the arable rotation. These values are less than our predicted results of N_2O emissions, equivalent to 3.66, 2.13 and 2.58 $Mg\ CO_2eq\ ha^{-1}y^{-1}$ for the arable rotation, SRC and Miscanthus, it should be noted that our predictions assumed annual fertilisation for optimum harvest.

The emissions of CH_4 from all systems were insignificant (<0.002 $Mg\ CO_2eq\ ha^{-1}y^{-1}$) in all cases. The emissions of N_2O derived from fuel combustion activities were highest from the arable rotation (2.08 $Mg\ CO_2eq\ ha^{-1}y^{-1}$) and ranged between 0.5 $Mg\ CO_2eq\ ha^{-1}y^{-1}$ for SRC (0.531) and Miscanthus (0.520) to 0.7 $Mg\ CO_2eq\ ha^{-1}y^{-1}$ for Sida (0.694) and Silphium (0.669). The reduced N_2O emission derived from fuel combustion activities in the perennial energy crops is caused by the reduced number of agricultural operations, as the plants are established only in year 1 and there is no annual tillage. N_2O emissions from other sources were similar for all systems, varying between 1.6 and 2.2 $Mg\ CO_2eq\ ha^{-1}y^{-1}$. Within the arable system, the observation that direct N_2O emissions represent 40% of all N_2O emissions is slightly higher than estimates of direct N_2O emissions representing 24% and 35% of all N_2O emissions in Canada and the USA respectively [46]. Our results indicate that direct N_2O emissions represented between 72-78% of all N_2O emissions for the perennial bioenergy systems.

4.1. Strategies to reduce N_2O emissions in arable agriculture

Nitrous oxide emissions represent a significant source of GHG emissions in agriculture, equivalent to 35% of agricultural GHG emissions in the UK [6], and it is the dominant source of emissions from the arable sector. As with the main arable sector, reducing direct N_2O emissions of perennial bioenergy systems would increase their value for supporting net zero targets. One way to achieve this would be intercropping with legumes, as investigated by Nabel *et al.* [36,37] .

Considering the two sources of N_2O emissions, direct and indirect, there would be a number of strategies to reduce them. First of all, N_2O

emissions would significantly decrease by reducing/removing fertilisation. Net GHG emissions obtained in the current model, where annual fertilisation was assumed, for Miscanthus are significantly higher (2.23 Mg CO_2eq ha^{-1} y^{-1}) compared with the GHG emissions resulted from a model [31] based on Terravesta Farms [47] commercial Miscanthus farming in the UK, where no fertilization is applied (-2.35 Mg CO_2eq $ha^{-1}y^{-1}$). If the analysed bioenergy crops had no annual fertilisation, direct N_2O emissions would decrease substantially (0.947, 1.46, 1.35, 1.33 Mg CO_2eq ha^{-1} y^{-1} for SRC, Miscanthus, Sida and Silphium, respectively) and overall net emissions would decrease accordingly (0.400, 1.628, 2.20, -1.465 Mg CO_2eq ha^{-1} y^{-1} for the rotation, SRC, Miscanthus, Sida and Silphium, respectively). This highlights the negative impact of manufactured N fertilisation on the predicted N_2O emissions of perennial bioenergy crops. A controlled long-term field experiment could expose how much N is needed to achieve attractive mature yields and allow N fertilisation rates to be optimised to meet environmental targets.

Reducing indirect N_2O emissions from managed soils could be achieved by reducing tillage, adopting reduced tillage practices such as strip-, minimum-, and zero-tillage [43]. Reducing N_2O emissions derived from on-farm fuel combustion could be achieved by using diesel tractors with lower emissions, or potentially tractors powered by electricity in the future. It is also affected by the choice of fertiliser type, e.g. urea generates higher ammonia emissions (EF=0.153 [30]) than ammonium nitrate (EF=0.06 [30]).

In our study, we purposely compared GHG fluxes from common agricultural crops with energy crops per unit area. If the take up of Sida and Silphium matches a pre-existing decline in arable crop areas, this would minimise the competition for land between agricultural and energy crops. However, if bioenergy crops are resulting in reduced agricultural crop production, this could lead to land use change elsewhere to meet current food demand [45]. An alternative scenario is that the demand for livestock products decreases, and this releases land for bioenergy crops [52].

4.2. Importance of this work to the energy nexus topic

In an era when it is more crucial than ever to reduce (and mitigate) the amount of GHG emissions that we generate, it is imperative that we fully understand the bioenergy options available, including novel bioenergy crops and their associated GHG emissions. Where it can be established that bioenergy crops are helpful in the reduction of GHG emissions, they can complement conventional agricultural crops to provide alternative/additional sources of income, especially by making use of less productive and marginal land. This work provides an initial understanding of the GHG fluxes associated with the establishment and cultivation of Sida and Silphium and shows that these novel bioenergy crops may potentially have a positive impact by fixing carbon in unharvested biomass and the unharvested roots and hence into long-term storage in soil.

4.3. Model limitations

We have identified the following limitations to the developed model: the model does not account for the manufacturing of any products or sourcing of materials before they reach the farm; the model does not account for the processing of any products beyond the farm gate; the underground biomass data of Sida was obtained after 1 year of cultivation, value that was taken as the mature underground biomass of the crop, which might not be representative of the underground biomass of an actual mature plantation (4 years old); it was assumed that the underground biomass of Sida increases annually by 6.5%, which might be different in reality. The end of use of biomass for Sida was solid fuel for combustion which affects litter production and increases CO_2 emissions accordingly.

5. Conclusions

Under the assumptions included in the current study, the GHG emissions model of the establishment and cultivation of Sida and Silphium suggests that their cultivation results respectively in the net emission and sequestration of GHG emissions. The two novel bioenergy systems were predicted to emit and sequester 2.9 and 0.6 Mg CO_2eq $ha^{-1}y^{-1}$ respectively. From the annual emissions of the studied systems (Table 9), the analysis predicts that the arable rotation and Sida released CO_2 to the atmosphere whilst the SRC, Miscanthus and Silphium systems were predicted to result in the net removal of CO_2. Silphium presents potential for carbon dioxide sequestration due to its overall C sequestration.

The current study demonstrated that when annual fertilisation is accounted for in the calculations, N_2O emissions can have a very large impact on the net GHG emissions balance over 16 years rotation of perennial bioenergy systems. N_2O emissions negatively affect the overall net GHG emissions balance by significantly reducing the carbon sequestration potential of perennial bioenergy systems and even shifting said balance from negative to positive. Therefore effective nitrogen management is crucial in achieving a carbon neutral or negative system. Minimising nitrogen fertilisation may be difficult for any crop to maintain productivity but we encourage active management of fertilisation, combining regular soil and plant analyses with enhancing N-use efficiency of crops, as well as management of crop residues.

The current study assumed an annual fertilisation regime with the objective of maximising biomass production. If the purpose of growing energy crops in general and of Sida and Silphium in particular is to minimise net GHG emissions, overall emissions should be considered in the decision making process. Having seen the results, the authors encourage the production of biomass from Sida to produce biogas, which could potentially sequester 2.3 Mg CO_2eq$ha^{-1}y^{-1}$. Calculations should also be completed to determine the appropriate nitrogen application rate for the crops. This environmentally optimum nitrogen application rate can be determined by estimating an economic cost of N_2O emissions. The assumptions included in the model regarding the underground biomass of the systems have a substantial impact in the mean net balance of emissions, and should be therefore validated with empirical data from mature research/commercial plantations to correct the model. In addition, we recommend that a GHG flux study should be completed to further investigate the validity of the model and provide enough data to generate calibration coefficients.

In addition, to have a complete picture of the environmental footprint associated with the production of Sida and Silphium biomass, we recommend carrying out a complete LCA of their cultivation (including manufacturing of inputs) and energy processing, comparing them with arable and other energy crops.

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Author Contribution Statement - Greenhouse gas emissions associated with the cultivation of two novel bioenergy crops in the UK

Laura Cumplido-Marin: Conceptualization, Methodology, Validation, Investigation, Data Curation, Writing – Original Draft, Visualization, Project administration. **Paul J. Burgess:** Supervision, Funding acquisition, Resources, Writing – Review & Editing, Visualization. **Anil**

R. Graves: Supervision, Funding acquisition, Resources, Writing – Review & Editing. **Adrian Williams:** Methodology, Validation, Writing – Review & Editing.

Declarations of interest

None.

CRediT authorship contribution statement

Laura Cumplido-Marin: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Anil R. Graves:** Supervision, Funding acquisition, Resources, Writing – review & editing. **Paul J. Burgess:** Supervision, Funding acquisition, Resources, Writing – review & editing, Visualization. **Adrian Williams:** Methodology, Validation, Writing – review & editing.

Data availability

The full model developed during the project can be accessed through Cranfield Online Research Data (CORD) repository system using the following link: DOI: 10.17862/cranfield.rd.18008363.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2022.100162.

Appendix

A1. IPCC greenhouse gas emissions overall methodology calculations

A1.1. Emissions from fuel combustion activities

$Emissions = \sum_j (Fuel_j * EF_j)$ *where: Emission = Emissions (kg); $Fuel_j$ = fuel consumed (as represented by fuel sold (TJ); EF_j = emission factor (kg TJ^{-1}); j = fuel type = diesel.*	Equation A 1 [23]

A1.2. Carbon stock change in biomass pool

$\Delta C_{CL} = \Delta C_B + \Delta C_{SO} + \Delta C_{LI}$ *where: ΔC_{CL} = carbon stock change in cropland; ΔC_B = carbon stock changes of biomass pool; ΔC_{SO} = carbon stock changes of soil pool; ΔC_{LI} = carbon stock changes of litter pool*	Equation A 2 [22]
$\Delta C_B = \Delta C_G - \Delta C_L$ *where: ΔC_B = annual change in carbon stocks in biomass pool; ΔC_G = annual increase in carbon stock due to biomass growth (t C y^{-1}); ΔC_L = annual decrease in carbon stock due to biomass loss (t C y^{-1})*	*Equation A 3* [22]
$\Delta C_G = \sum_{i,j} (A_{i,j} * G_{total_{i,j}} * CF_{i,j})$ *where: ΔC_G = annual increase in carbon stock due to biomass growth (t C y^{-1}); $A_{i,j}$ = area of land (ha); $G_{total\ I,j}$ = mean annual biomass growth (t DM ha^{-1} y^{-1}); $CF_{I,j}$ = carbon fraction of dry matter (t DM t DM^{-1})*	*Equation A 4* [22]
$G_{total} = \sum\{G_W * (1 + R)\}$ *where: G_{total} = average annual biomass growth, both above and below ground (t DM ha^{-1} y^{-1}); G_w = average annual above-ground biomass growth specific vegetation type (t DM ha^{-1} y^{-1}); R = ratio of below ground to above ground biomass ()*	*Equation A 5* [22]
$\Delta C_L = L_{disturbance}$ *where: ΔC_L = annual decrease in carbon stock due to biomass loss (t C y^{-1}); $L_{disturbance}$ = annual biomass carbon losses due to disturbances (t C y^{-1})*	*Equation A 6* [22]
$L_{disturbance} = \{A_{disturbance} * B_W * (1 + R) * CF * fd\}$ *where: $L_{disturbance}$ = annual biomass carbon losses due to disturbances (t C y^{-1}); $A_{disturbance}$ = area affected by disturbances (ha y^{-1}); B_W = average above-ground biomass affected by disturbances (t DM ha^{-1}); R = ratio of below-ground biomass to above-ground biomass (); CF = carbon fraction of dry matter (); fd = fraction of biomass lost in disturbance, fd=1 if whole stand replaced*	*Equation A 7* [22]

A1.3. Carbon stock change in mineral soil pool

$\Delta C_{SOILS} = \Delta C_{mineral}$ *where: ΔC_{SOILS} = annual change in carbon stock in dead organic matter (t C y^{-1}); $\Delta C_{mineral}$ = annual change in carbon stock in mineral soils (t C y^{-1})*	*Equation A 8* [22]
$\Delta C_{mineral} = (SOC_0 - SOC_{(0-T)})/D$ *SOC_0 = soil organic carbon stock in the last year of inventory (t C); $SOC_{(0-T)}$ = soil organic carbon stock at the beginning of the inventory (t C); SOC_0 and $SOC_{(0-T)}$ calculated using SOC equation (below); T = number of years over a single inventory time period (y); D = default time period for transition between equilibrium SOC values (y), commonly 20 years*	*Equation A 9* [22]
$SOC = \sum_{c,s,i} (SOC_{REF_{c,s,i}} * F_{LU_{c,s,i}} * F_{MG_{c,s,i}} * F_{I_{c,s,i}} * A_{c,s,i})$ *c = climate zones; s = soil types; i = set of management systems present in a country; SOC_{REF} = reference carbon stock (t C ha^{-1}), for a cold temperate moist climate region and low activity clay soil, SOC_{REF} = 85 t C ha^{-1}; F_{LU} = stock change factor for land-use systems for a particular land-use, dimensionless; F_{MG} = stock change factor for management regime, dimensionless; F_I = stock change factor for input of organic matter, dimensionless; A = land area (ha)*	*Equation A 10* [22]

A1.4. Carbon stock change in litter pool

$\Delta C_{DOM} = (A * ((DOM_{t2} - DOM_{t1})/T)) * CF$ *where: ΔC_{DOM} = annual change in carbon stock in litter pool (t C y^{-1}); A = area (ha); DOM_{t2} = litter stock at time t2 (t DM ha^{-}); DOM_{t1} = litter stock at time t1 (t DM ha^{-1}); T = (t2 – t1) = period of time between second stock estimate and first stock estimate (y); CF = carbon fraction of dry matter (t C), litter = 0.37*	*Equation A 11* [27]

A1.5. Direct N_2O emissions

$N_2O_{direct}N = N_2O - N_{Ninputs}$ where: N_2O_{direct} N = annual direct N_2O–N emissions produced from managed soils (kg N_2O–N y^{-1})	*Equation A 12* [25]
$N_2O - N_{inputs} = (F_{SN} + F_{CR} + F_{SOM}) * EF_1$ N_2O - N_{inputs} = annual direct N_2O–N emissions from N inputs to managed soils (kg N_2O–N y^{-1}); F_{SN} = annual amount of synthetic fertiliser N applied to soils (kg N y^{-1}); F_{CR} = annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils (kg N y^{-1}); F_{SOM} = annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management (kg N y^{-1}); EF_1 = emission factor for N_2O emissions from N inputs (kg N_2O N per kg N input) = 0.01	*Equation A 13* [25]
$F_{CR} = \sum_T \{[AGR_{(T)} * N_{AG(T)} * (1 - Frac_{remove(T)})] + [BGR_{(T)} * N_{BG(T)}]\}$ where: $AGR_{(T)}$ = annual above-ground crop residue for crop T (kg DM y^{-1}); $N_{AG(T)}$ = N content of above-ground residues for crop T (kg N per kg DM); $Frac_{remove(T)}$ = fraction of above-ground residues crop T removed annually, if not available assume no removal; $BGR_{(T)}$ = annual below-ground crop residue of crop t (kg DM y^{-1}); $N_{BG(T)}$ = N content of below-ground residues for crop T (kg N per kg DM)	*Equation A 14* [29]
$BGR_T = (Crop_{(T)} + AG_{DM(T)}) * RS_{(T)} * Area_{(T)} * Frac_{renew(T)}$ where: $Crop_{(T)}$ = harvested annual dry matter yield for crop T (kg DM ha^{-1}) = Fresh yield * DM (%); $AG_{DM(T)}$ = above-ground residue for crop T (kg DM ha^{-1}); $RS_{(T)}$ = ratio of below-ground residue to harvested yield of crop T (); $Area_{(T)}$ = total annual area harvested of crop T (ha y^{-1}); $Frac_{renew(T)}$ = fraction of total area under crop T renewed annually. Annual crops $Frac_{renew}$ = 1	*Equation A 15* [29]
$AG_{DM(T)} = Crop_{(T)} * R_{AG(T)}$ where: $R_{AG(T)}$ = ratio of above-ground residues dry matter ($AG_{DM(T)}$) to harvested yield	*Equation A 16* [29]
$F_{SOM} = \sum_{LU} [(\Delta C_{mineral,LU} * (1/R)) * 1000]$ where: F_{SOM} = the net annual amount of N mineralised in mineral soils as a result of loss of soil carbon through change in land use or management (kg N); $\Delta C_{mineral,LU}$ = average annual loss of soil carbon for each land-use type (t C); R = C:N ratio of the soil organic matter. Default value of 10 (range from 8 to 15) for changes on Cropland Remaining Cropland	*Equation A 17* [25]

A1.6. Indirect N_2O emissions

$N_2O_{(ATD)}N = [(F_{SN} * F_{rac_{GASF}})] * EF_4$ where: $N_2O_{(ATD)}$ N = annual amount of N_2O N produced from atmospheric deposition of N volatilised from managed soils (kg N_2O N y^{-1}); F_{SN} = annual amount of synthetic fertiliser N applied to soils (kg N y^{-1}); $Frac_{GASF}$ = fraction of synthetic fertiliser N that volatilises as NH_3 and NO_x (kg N volatilised per kg of N applied), default value = 0.10; EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg N_2O N per kg NH_3 N + NOx N volatilised, default value = 0.010	*Equation A 18* [25]
$N_2O_{(L)}N = (F_{SN} + F_{CR} + F_{SOM}) * Frac_{LEACH-H} * EF_5$ where: $N_2O_{(L)}$N = annual N_2O–N from leaching and runoff of N additions to managed soils (kg N_2O–N y^{-1}); F_{SN} = annual amount of synthetic fertiliser N applied to soils (kg N y^{-1}); F_{CR} = amount of N in crop residues (above and below ground), returned to soils annually (kg N y^{-1}); F_{SOM} = annual N mineralised in mineral soils associated with loss of soil C from soil organic matter as a result of changes to management (kg N y^{-1}); $Frac_{LEACH-H}$ = N fraction added to/mineralised in managed soils lost through leaching and runoff (kg N per kg of N additions), default = 0.30; EF_5 = emission factor for N_2O emissions from N leaching and runoff (kg N_2O–N per kg N leached and runoff), default = 0.0075	*Equation A 19* [25]

A2. Model calculations

A2.1. Summary

Table A1
Annual and life cycle emissions for all systems

Categories	Net CO_2 (kg CO_2 eq ha^{-1} y^{-1})	CH_4	N_2O	Total GHG emissions
1A4c Fuel combustion activities: Other sectors: Agriculture				
Wheat	492.887	1.728	1744.790	2239.405
Oats	492.887	1.728	1744.790	2239.405
OSR	253.881	0.890	898.722	1153.492
Sugar beet	1236.176	4.333	4375.988	5616.498
Forage maize	494.091	1.732	1749.051	2244.873
SRC (establishment)	422.822	1.482	1496.764	1921.068
SRC (recurring no harvest)	81.869	0.287	289.809	371.965
SRC (recurring harvest years)	232.080	0.813	821.547	1054.440
Miscanthus (establishment)	422.822	1.482	1496.764	1921.068
Miscanthus (recurring)	128.522	0.450	454.961	583.933
Sida (establishment)	494.573	1.734	1750.759	2247.066
Sida (recurring)	176.143	0.617	623.534	800.294
Silphium (establishment)	382.411	1.340	1353.711	1737.462
Silphium (recurring)	176.143	0.617	623.534	800.294
3B2a Carbon stock change				
> Biomass, above ground				
SRC	0.00	-	-	
Miscanthus	0.00	-	-	
Sida	0.00	-	-	
Silphium	0.00	-	-	
> Biomass, below ground				
SRC	-1446.296	-	-	
Miscanthus	-3590.837	-	-	
Sida (y1-y4)	-9852.991	-	-	
Sida (y5-onwards)	-640.444			
Silphium	-1371.002	-	-	
> Soil				
Arable crops	0.00	-	-	
Energy crops	-2284.509	-	-	
> Litter				
SRC (year 1)	2509.833	-	-	
SRC (year 2)	2509.833	-	-	
SRC (year 3)	2509.833	-	-	
SRC (year 4)	2509.833	-	-	
Miscanthus (year 1)	288.970	-	-	
Miscanthus (year 2)	1890.345	-	-	
Miscanthus (year 3)	5345.945	-	-	
Miscanthus (year 4 and onwards)	6040.276	-	-	
Sida (year 1)	985.709	-	-	
Sida (year 2)	3982.970	-	-	
Sida (year 3)	5262.465	-	-	
Sida (year 4 and onwards)	5594.941	-	-	
Silphium (year 1)	0.000	-	-	
Silphium (year 2)	0.000	-	-	
Silphium (year 3)	0.000	-	-	
Silphium (year 4)	0.000	-	-	
Silphium (year 5 and onwards)	0.000	-	-	
3C4 Direct N2O Emissions from Managed Soils				
wheat	-	-	1626.608	
oats	-	-	1179.810	
OSR	-	-	1672.194	
sugar beet	-	-	1517.557	
forage maize	-	-	1321.963	
SRC (year 1 – year 4)	-	-	1383.049	
SRC (year 5 - onwards)			1587.218	
Miscanthus	-	-	2007.559	
Sida	-	-	2006.540	
Silphium	-	-	2116.447	
3C5 Indirect N2O Emissions from Managed Soils				
wheat	-	-	121.847	
oats	-	-	83.369	
OSR	-	-	121.847	
sugar beet	-	-	100.043	
forage maize	-	-	96.195	
SRC	-	-	57.717	
Miscanthus	-	-	53.869	
Sida	-	-	64.130	
Silphium	-	-	76.956	

(*continued on next page*)

Table A1 (*continued*)

Categories	Net CO_2 (kg CO_2 eq ha^{-1} y^{-1})	CH_4	N_2O	Total GHG emissions				
	Annual emmissions (kg CO_2 eq ha^{-1})			Multiplier	**Life cycle emissions (t CO_2 eq ha^{-1})**			**TOTAL**
Rotation	**CO_2**	**CH_4**	**N_2O**		**CO_2**	**CH_4**	**N_2O**	
Wheat	492.887	1.728	3493.246	4	1.972	0.007	13.973	
Oats	492.887	1.728	3007.969	3	1.479	0.005	9.024	
OSR	253.881	0.890	2692.763	3	0.762	0.003	8.078	
Sugar beet	1236.176	4.333	5993.588	3	3.709	0.013	17.981	
Forage maize	494.091	1.732	3167.209	3	1.482	0.005	9.502	
Rotation			1147		9.403	0.0330	58.6	67.99
					Annual emissions (t CO2 eq $ha^{-1}y^{-1}$)			
					CO_2	**CH_4**	**N_2O**	**TOTAL**
				tonnes	0.588	2.08E-03	3.66	4.25
				kg	587.67	2.08	3659.8	4249.6
SRC	**Annual emmissions (kg CO_2 eq ha^{-1})**			Multiplier	**Life cycle emissions (t CO_2 eq ha^{-1})**			
Year	**CO_2**	**CH_4**	**N_2O**		**CO_2**	**CH_4**	**N_2O**	
1 (establishment)	-798.150	1.482	2937.529	1	-0.798	0.001	2.938	
2	-1139.104	1.482	1730.575	1	-1.139	0.001	1.731	
3	-1139.104	1.482	1730.575	1	-1.139	0.001	1.731	
4 (harvest)	-988.893	1.482	2262.313	1	-0.989	0.001	2.262	
5	-1139.104	1.482	1934.744	1	-1.139	0.001	1.935	
6	-1139.104	1.482	1934.744	1	-1.139	0.001	1.935	
7 (harvest)	-988.893	1.482	2466.482	1	-0.989	0.001	2.466	
8	-1139.104	1.482	1934.744	1	-1.139	0.001	1.935	
9	-1139.104	1.482	1934.744	1	-1.139	0.001	1.935	
10 (harvest)	-988.893	1.482	2466.482	1	-0.989	0.001	2.466	
11	-1139.104	1.482	1934.744	1	-1.139	0.001	1.935	
12	-1139.104	1.482	1934.744	1	-1.139	0.001	1.935	
13 (harvest)	-988.893	1.482	2466.482	1	-0.989	0.001	2.466	
14	-1139.104	1.482	1934.744	1	-1.139	0.001	1.935	
15	-1139.104	1.482	1934.744	1	-1.139	0.001	1.935	
16 (harvest)	-1139.104	1.482	2466.482	1	-1.139	0.001	2.466	
TOTAL			2125		-17.284	0.0237	34.0	16.74
					Annual emissions (t CO2 eq $ha^{-1}y^{-1}$)			
					CO_2	**CH_4**	**N_2O**	**TOTAL**
				tonnes	-1.08	1.48E-03	2.13	1.05
				kg	-1080.2		2125.3	
Miscanthus	**Annual emmissions (kg CO_2 eq ha^{-1})**			Multiplier	**Life cycle emissions (t CO_2 eq ha^{-1})**			
Year	**CO_2**	**CH_4**	**N_2O**		**CO_2**	**CH_4**	**N_2O**	
1 (establishment)	-5163.554	1.48E+00	3558.192	1	-5.164	0.0015	3.558	
2 (recurring)	-3856.478	4.50E-01	2516.389	1	-3.856	0.0005	2.516	
3 (recurring)	-400.879	4.50E-01	2516.389	1	-0.401	0.0005	2.516	
4 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
5 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
6 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
7 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
8 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
9 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
10 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
11 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
12 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
13 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
14 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
15 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
16 (recurring)	293.452	4.50E-01	2516.389	1	0.293	0.0005	2.516	
TOTAL	-350		2582		-5.606	0.00824	41.3	35.71
					Annual emissions (t CO2 eq $ha^{-1}y^{-1}$)			
					CO_2	**CH_4**	**N_2O**	**TOTAL**
				tonnes	-0.350	5.15E-04	2.58	2.23
				kg			2581.5	

(*continued on next page*)

Table A1 (*continued*)

Categories	Net CO_2 (kg CO_2 eq ha^{-1} y^{-1})	CH_4	N_2O	Total GHG emissions				
Sida	**Annual emmissions (kg CO_2 eq ha^{-1})**			Multiplier	**Life cycle emissions (t CO_2 eq ha^{-1})**			
Year	**CO_2**	**CH_4**	**N_2O**		**CO_2**	**CH_4**	**N_2O**	
1 (establishment)	-10657.219	1.73E+00	3821.429	1	-10.657	0.0017	3.821	
2 (recurring)	-7978.388	6.17E-01	2694.204	1	-7.978	0.0006	2.694	
3 (recurring)	-6698.893	6.17E-01	2694.204	1	-6.699	0.0006	2.694	
4 (recurring)	-6366.417	6.17E-01	2694.204	1	-6.366	0.0006	2.694	
5 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
6 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
7 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
8 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
9 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
10 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
11 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
12 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
13 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
14 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
15 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
16 (recurring)	2846.130	6.17E-01	2694.204	1	2.846	0.0006	2.694	
TOTAL					2.453	0.0110	44.2	46.70
					Annual emissions (t CO2 eq $ha^{-1}y^{-1}$)			
					CO_2	**CH_4**	**N_2O**	**TOTAL**
				tonnes	0.153	6.87E-04	2.76	2.92
				kg				
Silphium	**Annual emmissions (kg CO_2 eq ha^{-1})**			Multiplier	**Life cycle emissions (t CO_2 eq ha^{-1})**			
Year	**CO_2**	**CH_4**	**N_2O**		**CO_2**	**CH_4**	**N_2O**	
1 (establishment)	-3273.100	1.34E+00	3547.114	1	-3.273	0.0013	3.547	
2 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
3 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
4 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
5 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
6 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
7 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
8 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
9 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
10 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
11 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
12 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
13 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
14 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
15 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
16 (recurring)	-3479.368	6.17E-01	2816.937	1	-3.479	0.0006	2.817	
TOTAL					-55.464	0.0106	45.8	-9.65
					Annual emissions (t CO2 eq $ha^{-1}y^{-1}$)			
					CO_2	**CH_4**	**N_2O**	**TOTAL**
				tonnes	-3.47	6.63E-04	2.86	-0.603
				kg				

A2.2. Emissions from fuel combustion activities

Table A2
Diesel consumption during agricultural activity.

	Operation	Implement	Rated power (P)	Average fuel consumption (f_e)	Work rate (q_A)	Fuel consumption (f_A)	Multiplier	Mean diesel use per ha	Passes per season (n)	Diesel use per season
			(kW)	(l h^{-1})	(h ha^{-1})	(l ha^{-1})	()	(l ha^{-1})	()	(l ha^{-1})
Wheat										
Cultivation	Ploughing	Plough	142	36.581	1.1	33.255	1	33.255	1.2	39.906
	Power harrowing	Power harrow	167	43.021	2.0	21.511	1	21.511	0.6	12.906
	Rolling	Cambridge rolls	75	19.321	2.8	6.900	2	13.801	1.0	13.801
	Discing	Disc and pack	200	51.522	2.9	17.766	1	17.766	1.5	26.649
Drilling	Drilling	Drill	200	51.522	4.1	12.566	1	12.566	1.0	12.566
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.6	3.640
Harvesting	Combining cereals	Combine harvester	150	38.642	1.1	35.129	1	35.129	1.0	35.129
Baling	Baling	Baler	75	19.321	1.4	13.801	1	13.801	1.0	13.801
Carting	Carting	Carting trailer	75	19.321	4.2	4.600	1	4.600	2.0	9.200
Wheat - diesel total (l ha^{-1})										189.950
Oats										
Cultivation	Ploughing	Plough	142	36.581	1.1	33.255	1	33.255	1.2	39.906
	Power harrowing	Power harrow	167	43.021	2.0	21.511	1	21.511	0.6	12.906
	Rolling	Cambridge rolls	75	19.321	2.8	6.900	2	13.801	1.0	13.801
	Discing	Disc and pack	200	51.522	2.9	17.766	1	17.766	1.5	26.649
Drilling	Drilling	Drill	200	51.522	4.1	12.566	1	12.566	1.0	12.566
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.6	3.640
Harvesting	Combining cereals	Combine harvester	150	38.642	1.1	35.129	1	35.129	1.0	35.129
Baling	Baling	Baler	75	19.321	1.4	13.801	1	13.801	1.0	13.801
Carting	Carting	Carting trailer	75	19.321	4.2	4.600	1	4.600	2.0	9.200
Oats - diesel total (l ha^{-1})										189.950
OSR										
Cultivation	Cultivating	Cultivator	75	19.321	2.9	6.662	1	6.662	1.3	8.661
	Rolling	Cambridge rolls	75	19.321	2.8	6.900	1	6.900	1.0	6.900
Drilling	Drilling	Drill	200	51.522	4.1	12.566	1	12.566	1.0	12.566
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	4.8	29.124
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.9	5.461
Harvesting	OSR harvesting	Combine harvester	150	38.642	1.1	35.129	1	35.129	1.0	35.129
Carting	Carting	Carting trailer	75	19.321	3.5	5.520	1	5.520	1.0	5.520
OSR - diesel total (l ha^{-1})										97.84
Sugar beet										
Cultivation	Ploughing	Plough	142	36.581	1.1	33.255	1	33.255	1.3	43.232
	Cultivating	Cultivator	75	19.321	2.9	6.662	1	6.662	1.5	9.994
	Rolling	Cambridge rolls	75	19.321	2.8	6.900	1	6.900	1.0	6.900
Drilling	Drilling	Drill	200	51.522	1.3	39.632	1	39.632	1.0	39.632
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	11.8	71.596
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.6	3.640
Harvesting	Sugar beet harvesting	Sugar beet harvester	585	150.703	0.5	301.405	1	301.405	1.0	301.405
Carting	Carting	Carting trailer	75	19.321	12.9	1.498	1	1.498	1.0	1.498
Sugar beet - diesel total (l ha^{-1})										476.40
Forage maize										
Cultivation	Ploughing	Plough	142	36.581	1.1	33.255	1	33.255	1.3	43.232
	Rolling	Cambridge rolls	75	19.321	2.8	6.900	1	6.900	1.0	6.900
Seedbed prep and drilling	Cultivating	Cultivator	75	19.321	2.9	6.662	1	6.662	1.2	7.995
	Power harrowing	Power harrow	167	43.021	2.0	21.511	1	21.511	0.9	19.359
	Drilling	Drill	200	51.522	4.1	12.566	1	12.566	1.0	12.566
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	7.0	42.472
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820
Harvesting	Forage harvesting	Forage harvester	370	95.316	1.7	56.068	1	56.068	1.0	56.068
Carting	Carting	Carting trailer	75	19.321	10.2	1.894	1	1.894	2.0	3.788
Forage maize - diesel total (l ha^{-1})										190.41

(*continued on next page*)

Table A2 (*continued*)

	Operation	Implement	Rated power (P) (kW)	Average fuel consumption (f_e) (l h^{-1})	Work rate (q_A) (h ha^{-1})	Fuel consumption (f_A) (l ha^{-1})	Multiplier ()	Mean diesel use per ha (l ha^{-1})	Passes per season (n) ()	Diesel use per season (l ha^{-1})
SRC (establishment year)										
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
Cultivation	Ploughing	Plough	142	36.581	1.1	33.255	1	33.255	1.3	43.232
	Subsoiling	Subsoiler	200	51.522	2.4	21.468	1	21.468	0.2	4.294
	Power harrowing	Power harrow	167	43.021	2.0	21.511	1	21.511	0.9	19.359
	Rolling	Cambridge rolls	75	19.321	2.8	6.900	1	6.900	1.0	6.900
Planting	Potato planting	Potato planter	200	51.522	1.3	39.632	1	39.632	1.0	39.632
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820
Mowing	Mowing	Mower	69	17.775	1.1	16.159	1	16.159	1.0	16.159
SRC (establishment year - diesel total (l ha^{-1})										162.95
SRC (no harvest years)										
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
SRC (no harvest years) - diesel total (l ha^{-1})										**31.55**
SRC (harvest years)										
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820
Harvesting	Forage harvesting	Forage harvester	370	95.316	1.7	56.068	1	56.068	1.0	56.068
Carting	Carting	Carting trailer	75	19.321	10.2	1.894	1	1.894	2.0	3.788
SRC (harvest years) - diesel total (l ha^{-1})										89.44
Miscanthus (establishment year)										
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
Cultivation	Ploughing	Plough	142	36.581	1.1	33.255	1	33.255	1.3	43.232
	Subsoiling	Subsoiler	200	51.522	2.4	21.468	1	21.468	0.2	4.294
	Power harrowing	Power harrow	167	43.021	2.0	21.5110	1	21.511	0.9	19.359
	Rolling	Cambridge rolls	75	19.321	2.8	6.90	1	6.900	1.0	6.900
Planting	Potato planting	Potato planter	200	51.522	1.3	39.632	1	39.632	1.0	39.632
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820
Mowing	Mowing	Mower	69	17.775	1.1	16.159	1	16.159	1.0	16.159
Miscanthus (establishment year) - diesel total (l ha^{-1})										162.95
Miscanthus (recurring)										
Spraying	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820
Mowing	Mowing	Mower	69	17.775	1.1	16.159	1	16.159	1.0	16.159
Carting	Carting	Carting trailer	75	19.321	10.2	1.894	1	1.894	2.0	3.788
Miscanthus (recurring) - diesel total (l ha^{-1})										49.53
Sida (establishment year)										
	Operation	**Implement**	**Engine power** (kW)	**Average fuel consumption (f_e)** (l h^{-1})	**Work rate (q_A)** (h ha^{-1})	**Fuel consumption (f_A)** (l ha^{-1})	**Multiplier** ()	**Mean diesel use per ha** (l ha^{-1})	**Passes per season** ()	**Diesel use per season** (l ha^{-1})
	Spraying	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
Cultivation	Ploughing	Tractor 200 kW	200	51.522	1.1	46.838	1	46.838	1.3	60.890
	Subsoiling	Subsoiler	200	51.522	2.4	21.468	1	21.468	0.2	4.294
	Power harrowing	Power harrow	167	43.021	2.0	21.511	1	21.511	0.9	19.359
	Rolling	Cambridge rolls	75	19.321	2.8	6.900	1	6.900	1.0	6.900
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820
Planting	Potato planting	Potato planter	200	51.522	1.3	39.632	1	39.632	1.0	39.632
Mechanical weeding	Cultivating	Cultivator	75	19.321	2.9	6.662	1	6.662	1.5	9.994
Mowing	Mowing	Mower	69	17.775	1.1	16.159	1	16.159	1.0	16.159
Sida (establishment year) - diesel total (l ha^{-1})										190.60
Sida (recurring)										
Mechanical weeding	Cultivating	Cultivator	75	19.321	2.9	6.662	1	6.662	1.5	9.994
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820
Harvesting	Forage harvesting	Forage harvester	370	95.316	1.7	56.068	1	56.068	1.0	56.068
Carting	Carting	Carting trailer	75	19.321	10.2	1.894	1	1.894	2.0	3.788
Sida (recurring) - Diesel Total (l ha^{-1})										67.88
Silphium (establishment year)										
Spraying	Spraying	Self propelled sprayer	179	46.112	7.6	6.067	1	6.067	5.2	31.551
Cultivation	Ploughing	Tractor 200 kW	200	51.522	1.1	46.838	1	46.838	1.3	60.890
	Subsoiling	Subsoiler	200	51.522	2.4	21.468	1	21.468	0.2	4.294
	Power harrowing	Power harrow	167	43.021	2.0	21.511	1	21.511	0.9	19.359
	Rolling	Cambridge rolls	75	19.321	2.8	6.900	1	6.900	1.0	6.900
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820

(*continued on next page*)

Table A2 (*continued*)

	Operation	Implement	Rated power (P) (kW)	Average fuel consumption (f_e) (l h^{-1})	Work rate (q_A) (h ha^{-1})	Fuel consumption (f_A) (l ha^{-1})	Multiplier ()	Mean diesel use per ha (l ha^{-1})	Passes per season (n) ()	Diesel use per season (l ha^{-1})
Seedbed prep and sowing	Drilling	Drill	200	51.522	4.1	12.566	1	12.566	1.0	12.566
Mechanical weeding	Cultivating	Cultivator	75	19.321	2.9	6.662	1	6.662	1.5	9.994
Diesel Total (l ha^{-1})										147.37
Silphium (recurring)										
Mechanical weeding	Cultivating	Cultivator	75	19.321	2.9	6.662	1	6.662	1.5	9.994
Fertilising	Fertilising	Self pro. sprayer	179	46.112	7.6	6.067	1	6.067	0.3	1.820
Harvesting	Forage harvesting	Forage harvester	370	95.316	1.7	56.068	1	56.068	1.0	56.068
Carting	Carting	Carting trailer	75	19.321	10.2	1.894	1	1.894	2.0	3.788
Silphium (recurring) - Diesel Total (l ha^{-1})										67.88

Table A3
Emissions derived from diesel consumption during agricultural activity.

Sector	Energy
Category	Fuel combustion activities
Category Code	1A4c Other sectors: Agriculture
Sheet	1 of 4 (CO2, CH4 and N2O from fuel combustion by source categories – Tier 1)

	Energy consumption				**CO2**		**CH4**		**N2O**
Liquid fuels: Gas / Diesel Oil	A Consumption (Mass, Volume or Energy unit)	B Conversion Factor (MJ/litre)	C Consumption (MJ)	D CO2 Emission Factor (kg CO2/MJ)	E CO2 Emissions (kg CO2)	F CH4 Emission Factor (kg CH4/MJ)	G CH4 Emissions (kg CH4)	H N2O Emission Factor (kg N2O /MJ)	I N2OEmissions (kg N2O)
			C=A*B		**E=C*D**		**G=C*F**		**I=C*H**
CROP									
Wheat	189.950	36.380	6910.441	0.071	492.887	8.333E-06	0.058	9.528E-04	6.584
Oats	189.950	36.380	6910.441	0.071	492.887	8.333E-06	0.058	9.528E-04	6.584
OSR	97.841	36.380	3559.491	0.071	253.881	8.333E-06	0.030	9.528E-04	3.391
Sugar beet	476.399	36.380	17331.600	0.071	1236.176	8.333E-06	0.14	9.528E-04	16.513
Forage maize	190.413	36.380	6927.315	0.071	494.091	8.333E-06	0.058	9.528E-04	6.600
SRC (establishment)	162.948	36.380	5928.104	0.071	422.822	8.333E-06	0.049	9.528E-04	5.648
SRC (recurring no harvest)	31.551	36.380	1147.823	0.071	81.869	8.333E-06	0.010	9.528E-04	1.094
SRC (recurring harvest years)	89.439	36.380	3253.832	0.071	232.080	8.333E-06	0.027	9.528E-04	3.100
Miscanthus (establishment)	162.948	36.380	5928.104	0.071	422.822	8.333E-06	0.049	9.528E-04	5.648
Miscanthus (recurring)	49.530	36.380	1801.924	0.071	128.522	8.333E-06	0.015	9.528E-04	1.717
Sida (establishment)	190.599	36.380	6934.081	0.071	494.573	8.333E-06	0.058	9.528E-04	6.607
Sida (recurring)	67.882	36.380	2469.578	0.071	176.143	8.333E-06	0.021	9.528E-04	2.353
Silphium (establishment)	147.374	36.380	5361.525	0.071	382.411	8.333E-06	0.045	9.528E-04	5.108
Silphium (recurring)	67.882	36.380	2469.578	0.071	176.143	8.333E-06	0.021	9.528E-04	2.353

A2.3. Stock changes in mineral soil pool

Table A4
Mineral Soil Organic C stock at the beginning of the inventory time period.

System	$A_{(0\text{-}T)}$	SOC_{ref}	F_{LU}	F_{MG}	F_I	$SOC_{(0\text{-}T)}$
arable	1	76	0.70	1.00	1.00	53.200
energy	-	-	-	-	-	53.200

Table A5
Mineral Soil Organic C stock in the last year of the inventory time period.

System	$A_{(0)}$	SO_{Cref}	F_{LU}	F_{MG}	F_I	$SOC_{(0)}$
arable	1	76	0.70	1.00	1.00	53.200
energy	1	76	0.72	1.04	1.11	63.169

Table A6
Stock changes in mineral soil pool for the considered period.

System	$SOC_{(0)}$	$SOC_{(0\text{-}T)}$	D	$\Delta C_{Mineral}$
arable	53.200	53.200	16	0.000
energy	63.169	53.200	16	0.623

A2.3. Stock changes in biomass pool

Table A7
Stock changes in biomass soil pool (above ground).

	G_w (t DM ha^{-1} y^{-1})	R ()	G_{total} (t DM ha^{-1} y^{-1})	A (ha)	CF ()	ΔC_G (t C y^{-1})	$A_{disturbance}$ (ha^{-1} y^{-1})	B_w (t DM ha^{-1})	R ()	CF ()	fd ()	ΔC_L (t C y^{-1})	ΔC_B (t C y^{-1})
SRC (year 1)	0.0	0.127	0.000	1.000	0.50	0.000	0.000	0.0	0.127	0.50	1.000	0.000	0.000
SRC (year 2)	10.0	0.127	11.270	1.000	0.50	5.635	0.000	0.0	0.127	0.50	1.000	0.000	5.635
SRC (year 3)	10.0	0.127	11.270	1.000	0.50	5.635	0.000	0.0	0.127	0.50	1.000	0.000	5.635
SRC (year 4 and onwards)	10.0	0.127	11.270	1.000	0.50	5.635	1.000	30.0	0.127	0.50	1.000	16.905	-11.270
Miscanthus (year 1)	0.6	0.389	0.833	1.000	0.47	0.392	1.000	0.600	0.389	0.47	1.00	0.392	0.000
Miscanthus (year 2)	3.92	0.389	5.452	1.000	0.47	2.563	1.000	3.925	0.389	0.47	1.00	2.563	0.000
Miscanthus (year 3)	11.1	0.389	15.419	1.000	0.47	7.247	1.000	11.100	0.389	0.47	1.00	7.247	0.000
Miscanthus (year 4 and onwards)	12.5	0.389	17.422	1.000	0.47	8.188	1.000	12.542	0.389	0.47	1.00	8.188	0.000
Sida (year 1)	2.0	2.350	6.856	1.000	0.47	3.222	1.000	2.047	2.350	0.47	1.00	3.222	0.000
Sida (year 2)	8.3	2.350	27.705	1.000	0.47	13.021	1.000	8.270	2.350	0.47	1.00	13.021	0.000
Sida (year 3)	10.9	2.350	36.604	1.000	0.47	17.204	1.000	10.927	2.350	0.47	1.00	17.204	0.000
Sida (year 4 and onwards)	11.6	2.350	38.917	1.000	0.47	18.291	1.000	11.617	2.350	0.47	1.00	18.291	0.000
Silphium (year 1)	0.0	0.515	0.000	1.000	0.47	0.000	1.000	0.000	0.515	0.47	1.00	0.000	0.000
Silphium (year 2)	9.9	0.515	15.052	1.000	0.47	7.075	1.000	9.933	0.515	0.47	1.00	7.075	0.000
Silphium (year 3)	14.7	0.515	22.275	1.000	0.47	10.469	1.000	14.700	0.515	0.47	1.00	10.469	0.000
Silphium (year 4)	15.7	0.515	23.841	1.000	0.47	11.205	1.000	15.733	0.515	0.47	1.00	11.205	0.000
Silphium (year 5* and onwards)	16.3	0.515	24.700	1.000	0.47	11.609	1.000	16.300	0.515	0.47	1.00	11.609	0.000

*It is considered that perennial crops such as Sida and Silphium reach maturity on the 4th year of cultivation, which becomes year 5 for Silphium since the 1st year this crop only grows a rosette.

Table A8
Stock changes in biomass soil pool (below ground).

	G_w (t DM ha^{-1} y^{-1})	R ()	G_{total} (t DM ha^{-1} y^{-1})	A (ha)	CF ()	ΔC_G (t C y^{-1})	$A_{disturbance}$ (ha^{-1} y^{-1})	B_w (t DM ha^{-1})	R ()	CF ()	fd ()	ΔC_L (t C y^{-1})	ΔC_B (t C y^{-1})
SRC	0.700	0.127	0.789	1.000	0.50	0.394	0.000	0.000	0.127	0.50	1.0	0.000	0.394
Miscanthus	1.500	0.389	2.084	1.000	0.47	0.979	0.000	1.500	0.389	0.47	1.0	0.000	0.979
$Sida_{y1\text{-}y4}$	1.707	2.350	5.717	1.000	0.47	2.687	0.000	1.707	2.350	0.47	1.0	0.000	2.687
$Sida_{y5\text{-}onwards}$	1.707	2.350	0.372	1.000	0.47	0.175	0.000	1.707	2.3550	0.47	1.0	0.000	0.175
Silphium	0.525	0.515	0.796	1.000	0.47	0.374	0.000	0.525	0.515	0.47	1.0	0.000	0.374

A2.4. Stock changes in litter pool

Table A9
Stock changes in litter pool.

	A (ha)	DOM_{t1} (tonnes DM ha^{-1})	DOM_{t2} (tonnes DM ha^{-1})	T (y)	CF ()	ΔC_{DOM} (tonnes C yr^{-1})
SRC (year 1)	1.000	0.000	1.850	1	0.370	0.685
SRC (year 2)	1.000	1.850	3.700	1	0.370	0.685
SRC (year 3)	1.000	3.700	5.550	1	0.370	0.685
SRC (year 4)	1.000	5.550	7.400	1	0.370	0.685
Miscanthus (year 1)	1.000	0.000	0.213	1	0.370	0.079
Miscanthus (year 2)	1.000	0.000	1.393	1	0.370	0.516
Miscanthus (year 3)	1.000	0.000	3.941	1	0.370	1.458
Miscanthus (year 4)	1.000	0.000	4.452	1	0.370	1.647
Sida (year 1)	1.000	0.000	0.727	1	0.370	0.269
Sida (year 2)	1.000	0.000	2.936	1	0.370	1.086
Sida (year 3)	1.000	0.000	3.879	1	0.370	1.435
Sida (year 4)	1.000	0.000	4.124	1	0.370	1.526
Silphium (year 1)	1.000	0.000	0.000	1	0.370	0.000
Silphium (year 2)	1.000	0.000	0.000	1	0.370	0.000
Silphium (year 3)	1.000	0.000	0.000	1	0.370	0.000
Silphium (year 4)	1.000	0.000	0.000	1	0.370	0.000
Silphium (year 5)	1.000	0.000	0.000	1	0.370	0.000

A2.5. Direct N_2O emissions

Table A10
Direct N_2O emissions.

	F_{SN} (kg ha^{-1})	$AGR_{(T)}$ (kg DM y^{-1})	$N_{AG(T)}$ ()	$Frac_{remove(T)}$ ()	Yield Fresh (kg DM ha^{-1})	DRY (%)	$Crop_{(T)}$ (kg ha^{-1})	$R_{AG(T)}$ ()	$AG_{DM(T)}$ (kg DM ha^{-1})	$RS_{(T)}$ ()	$Frac_{renew(T)}$ ()	$BGR_{(T)}$ (kg DM y^{-1})	$N_{BG(T)}$ ()	F_{CR} (kg N y^{-1})	F_{SOM} (kg N y^{-1})	EF_1 ()	$N_2O_{-N\ inputs}$ (kg N_2O N y^{-1})
Wheat	190	3900	0.006	0.000	8300	0.890	7387	1.300	9603	0.230	1.0	3908	0.009	58.570	0.000	0.0157	3.906
Oats	130	3500	0.007	0.000	6300	0.890	5607	1.300	7289	0.250	1.0	3224	0.008	50.292	0.000	0.0157	2.833
OSR	190	2600	0.015	0.000	3500	0.900	3150	0.300	945	0.540	1.0	2211	0.012	65.536	0.000	0.0157	4.016
Sugar beet	156	500	0.019	0.000	77000	0.220	16940	0.400	6776	0.200	1.0	4743	0.014	75.905	0.000	0.0157	3.644
Forage maize	150	3310	0.006	0.000	12000	0.870	10440	1.000	10440	0.220	1.0	4594	0.007	52.015	0.000	0.0157	3.175
$SRC_{y1\text{-}y4}$	90	1850	0.015	0.000	-	-	30000	0.300	9000	0.800	0.25	7800	0.012	121.350	0.000	0.0157	3.321
$SRC_{y5\text{-}onwards}$	90	1850	0.015	0.000	-	-	30000	0.300	9000	0.800	0.33	10400	0.012	152.550	0.000	0.0157	3.812
Miscanthus	84	4452	0.015	0.000	-	-	12500	0.300	9000	0.800	1.0	10400	0.012	222.784	0.000	0.0157	4.821
Sida	100	4124	0.015	0.000	-	-	11600	0.300	3750	0.800	1.0	13000	0.012	206.629	0.000	0.0157	4.818
Silphium	120	0	0.015	0.000	-	-	16300	0.300	3480	0.800	1.0	12064	0.012	203.424	0.000	0.0157	5.082

A2.6. Indirect N_2O emissions (from atmospheric deposition and leaching/run off)

Table A11
Indirect N_2O emissions due to atmospheric deposition.

	F_{SN} (kg N y^{-1})	$Frac_{GASF}$ ()	EF_4 ()	$N_2O_{(ATD)}N$ kg N_2O N y^{-1}
Wheat	190	0.110	0.014	0.293
Oats	130	0.110	0.014	0.200
OSR	190	0.110	0.014	0.293
Sugar beet	156	0.110	0.014	0.240
Forage maize	150	0.110	0.014	0.231
SRC	90	0.110	0.014	0.139
Miscanthus	84	0.110	0.014	0.129
Sida	100	0.110	0.014	0.154
Silphium	120	0.110	0.014	0.185

Table A12
Indirect N_2O emissions due to leaching.

	F_{SN} (kg N y^{-1})	F_{CR} (kg N y^{-1})	F_{SOM} (kg N y^{-1})	$Frac_{LEACH-(H)}$ ()	EF_5 ()	$N_2O_{(L)}N$ (kg N_2O N y^{-1})
Wheat	190	58.570	0.000	0.240	0.011	0.656
Oats	130	75.905	0.000	0.240	0.011	0.544
OSR	190	222.784	0.000	0.240	0.011	1.090
Sugar beet	156	75.905	0.000	0.240	0.011	0.612
Forage maize	150	52.015	0.000	0.240	0.011	0.533
SRC	90	0.000	0.000	0.240	0.011	0.238
Miscanthus	84	0.000	0.000	0.240	0.011	0.222
Sida	100	0.000	0.000	0.240	0.011	0.264
Silphium	120	0.000	0.000	0.240	0.011	0.317

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